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Collapsible Temporary Housing Design and Optimization

Jack Thomas Nigro
Worcester Polytechnic Institute

Michael James Morlock
Worcester Polytechnic Institute

Nasjela Thodhoraqi
Worcester Polytechnic Institute

Reid Billings
Worcester Polytechnic Institute

Ryan Judson Rigney
Worcester Polytechnic Institute

Semi-Collapsible Temporary Housing for Hurricane Relief and Recovery

A Major Qualifying Project Report submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfilment of the requirements for the Degree of Bachelor of Science

Submitted to: Professor Sarah Wodin-Schwartz

Department of Mechanical Engineering

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Reid Billings, Michael Morlock, Jack Nigro, Ryan Rigney, Nasjela Thodhoraqi
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Abstract

In the wake of a hurricane, relief organizations often provide victims with temporary housing until their original homes are repaired or replaced. Many current temporary housing solutions can accommodate displaced persons for up to one year, but these products can be expensive to manufacture, difficult to set up, and not reusable. This project, sponsored by Deployed Resources, addressed these shortcomings through the development of a cost-effective, semi-collapsible, and reusable temporary housing unit. The design incorporates three nested compartments which extend from an 8 x 10 ft collapsed size to a 10 x 22.5 ft expanded size. The unit is designed to accommodate four persons and includes permanently installed bathroom and kitchen appliances to minimize set-up time. Based on unit dimensions and weight, up to five units may be transported on a single trailer. The estimated manufacturing cost of each unit is $15,000. The team managed construction of a full-scale prototype of the unit at the Deployed Resources facility in Rome, NY.

Chapter 1: Introduction

The goal of this Major Qualifying Project was to design, build, and test a semi-collapsible temporary housing unit for use in hurricane relief and recovery. Deployed Resources, a company located in Rome, New York that specializes in temporary facilities and logistics, sponsored the team and provided a materials and travel budget.

Through research and interviews with specialists in the field of temporary housing, the team identified areas where current housing solutions fall short. Specifically, the team's primary goals were to design a product large enough to accommodate four people for up to one year, that can collapse to a size and weight that would allow for shipping multiple units at once, and cost less than $15,000 to manufacture.

The unit consists of three compartments that nest within the largest compartment, resulting in a minimum footprint of 8 x 10 ft (2.4 x 3.0 m). Fully expanded, the unit has a footprint of 22.5 x 10 ft (6.9 x 3.0 m). The design allows for a kitchen and bathroom as well as required wiring and piping connections to be permanently installed within the unit. A full-scale prototype of the unit was constructed at the Deployed Resources facility. Recommendations stemming from the prototyping process were provided to Deployed Resources and are included at the end of this report.

The design has received a provisional patent from the United States Patent and Trademark Office (USPTO) with the help of the WPI Intellectual Property (IP) office. The unique feature of the design is the one or more compartments sliding out of the main section utilizing tracks on the floor and fold-down walls of the unit. There are a myriad of potential uses for this design beyond disaster relief temporary housing. Due to the small shipping size, expanded size, and ease of set-up, this product could be used for mobile storefronts, hospitality areas, clinics, offices, etc.

Chapter 2: Sponsor/Client

The sponsor of this project is Deployed Resources LLC. Founded in 2001 in Rome, NY, Deployed Resources manufactures temporary and collapsible structures for government, commercial, industrial, and disaster relief applications. Deployed Resources' temporary solutions and services include large-scale camps, temporary housing or facilities, and temporary sanitary systems. Their disaster response temporary housing units aim to provide shelter from the elements, potable drinking water, and sanitary facilities. Units may be used during natural disasters, civil disputes, mass gatherings, or military maneuvers. Depending on the need, these units may be in use for up to one year. When a disaster strikes, Deployed Resources works with the Federal Emergency Management Agency (FEMA) to help determine where shelters should be sent, what types of shelters are needed, and how to improve shelters for the future. As a part of this collaboration, FEMA may rent or buy temporary housing units from Deployed Resources and provide them to people whose homes have suffered extensive damage that cannot be quickly repaired.

Deployed Resources is currently developing new disaster relief temporary housing solutions. They have identified comfort, aesthetics, running water, climate control, power, and protection from the elements as primary attributes for temporary housing. Areas of improvement on their existing temporary housing include but are not limited to: collapsibility, set up time, price, weight, storage, life expectancy, and modulation. Deployed Resources has agreed to sponsor this project to conduct research and design a new collapsible temporary housing solution that improves upon these areas. The WPI students will receive technical support and mentoring along with an initial budget from Deployed Resources to ensure a final design recommendation is delivered based on a full-scale prototype and analytical report.

Chapter 3: Background

Disaster relief shelters are roofed, secure, hygienic, and livable locations for people to utilize during periods of disaster until they are able to move back to their permanent homes (Bashawri, 2014). Many of these shelters are lightweight structures designed to be erected, dismantled and stored for future use. They include tents, prefabricated housing, and public community buildings such as leisure centers, universities, places of worship, sports venues and private rentals. Disaster relief shelters are broken down into categories such as emergency shelters, transitional shelters, temporary shelters, and temporary housing. This project will focus on temporary housing, a type of shelter used for six months to three years at a time. These could be prefabricated units utilized by relocated families while their permanent dwellings undergo repairs.

Over the past decade, various organizations dedicated to disaster response and recovery have researched and developed temporary housing units to address the issue of providing shelter for disaster relief efforts. An important distinction is the difference between a shelter and a temporary home. A shelter is typically a short-term solution on a large scale. A well-known example from Hurricane Katrina is the use of the Superdome, a 75,000-seat stadium in downtown New Orleans. Relief organizations like FEMA and Red Cross typically set up shelters in stadiums, churches, schools, warehouses, or any other buildings with a large footprint capable of taking in as many victims as possible. This strategy is unsustainable beyond the weeks immediately following a disaster, as crowded, open spaces do not provide the comfort or privacy necessary for longer-term housing.

3.1 Examples of Existing Temporary Housing Solutions

The current state of temporary housing technology has yet to adequately address the following issues (Rich Stapleton, personal communication, September 21, 2017):

- Cost of manufacturing
- Storage capabilities
- Reusability
- Modularity (ability to connect multiple units together)
- Occupant health and safety

The following sections summarize a sampling of past temporary housing efforts, highlighting the benefits and shortcomings of each design.

3.1.1 FEMA Manufactured Homes

During the Hurricane Katrina response, FEMA received criticism for the condition of manufactured homes they provided as temporary housing to displaced victims. These non-collapsible housing units were built on towing trailers and resemble recreational vehicles (RV's) in size and layout. The manufactured homes provide a comfortable living atmosphere and include advanced safety features, such as sprinklers and smoke detection. Despite these features, the units were built with manufacturing speed, not quality, as the driving force. In the hurry to mass-produce the units, FEMA significantly overpaid for them (Jansen, 2017). The U.S. Government Accountability Office (GAO) projects that FEMA paid $239,000 for each 280 ft^2 (26.0 m^2) unit, the same cost as a 2,000 ft^2 (185.8 m^2) home in Jackson, Mississippi. The GAO also reports that FEMA spent an estimated $30 million on overpriced contractor bids, and on maintenance inspections that never took place (U.S. GAO, 2007). Storage of unused units costs FEMA $130 million annually (Smith, 2015). Figure 1 shows a series of manufactured homes set up by FEMA following Hurricane Katrina.

Figure 1: Several manufactured homes set up by FEMA after Hurricane Katrina

The negative effects of the expedited manufacturing process stretched beyond economic consequences. Despite formaldehyde's classification as a carcinogen by the National Institute of Health, the U.S. Department of Housing and Urban Development (HUD) had no regulation for formaldehyde levels in travel trailers, since these occupancies are intended for temporary use only (Smith, 2015). The FEMA units were never intended to house displaced families for more than a year, but as of 2010, five years after moving in, many families were still in the manufactured homes because they had not raised enough money to rebuild or relocate (Smith, 2015). During this time, they faced exposure to formaldehyde levels up to 75 times the threshold for workplace safety, as shown by results from a FEMA test in 2006 (Smith, 2015).

In addition to financial and health concerns, the FEMA manufactured homes are not modular or collapsible. There is no convenient way to store them by either collapsing or stacking them; this contributes to the significant storage costs.

3.1.2 Collapsible Fiberglass Unit (CFU) Solution

The Collapsible Fiberglass Unit (CFU) is intended to serve as a rapid, foldable temporary housing solution. The CFU design is currently in Deployed Resources' inventory and is attractive for applications requiring quick set-up time and efficient transportation. The structure requires 3 to 4 hours to set-up and utilizes a forklift (Rich Stapleton, personal communication, September 21, 2017). The set-up process requires folding of the walls and roof in a particular order, as marked by small notes on the corner of each component (see Figure 2):

Figure 2: Assembly instructions on the walls of a CFU

This set-up process is error prone due to the required specific assembly sequence. If a wall is folded out of order, a hinge will often break or a breaker switch on an electric panel will be damaged (Rich Stapleton, personal communication, November 7, 2017). Also, the CFU's do not include any internal features. Once the structure is assembled, all contents such as furniture and appliances must be brought in from an outside source. These additional items require separate storage and therefore diminish the overall value of the CFU's minimized storage size.

Currently, Deployed Resources primarily uses the CFU's as rentals to music festivals and other events with the need for temporary structures. The company has considered using CFU's during disaster recovery but faces the following issues with distributing the units on such a large scale:

- *Modularity* - The CFU lacks the capability to connect to other units in order to create structures of larger size.
- *Cost* - At $30,000 per unit, the CFU currently exceeds the desired manufacturing cost for a mass-produced temporary housing unit.

3.1.3 Collapsible Modular Unit (CMU) Solution

The Collapsible Modular Unit (CMU) is the other primary temporary housing unit used by Deployed Resources. This design consists of a main structure similar to an 8x10 ft (2.4x3.0 m) shipping container and includes the standard shipping container corner castings. This allows the units to be easily transported and stacked for storage. The CMU's also have removable wall panels that enable users to connect multiple units together, creating larger footprints. Like CFU's, the collapsed CMU does not contain any furniture or appliances; these items must be stored and supplied separately. Each time the units are collapsed and setup again, new bolts must be drilled through the plastic flooring. This limits the number of possible uses and also decreases the structural stability of the flooring (Rich Stapleton, personal communication, November 7, 2017). Due to these factors, Deployed Resources has begun to use the CMU's only as permanent, non-collapsible units. Figure 3 shows the exterior and interior of connected CMU's.

Figure 3: Exterior (left) and interior (right) views of connection CMU's

3.1.4 IKEA Solution

In 2013, IKEA, a company specializing in ready-to-assemble furniture, released a design for a flat-pack refugee shelter. The design consists of just 68 components, costs $1,250, and takes about four hours for four people to assemble without expert knowledge. The shelter can hold up to five people and includes a solar panel. The design, called "Better Shelter", earned the London Design Museum's 2016 Beazley Design of the Year award. Jana Scholze, an associate professor of curating contemporary design at Kingston University (UK) and a juror for the award, said, "Better Shelter tackles one of the defining issues of the moment: providing shelter in an exceptional situation whether caused by violence or disaster" (Alleyne, 2017). Figure 4 shows the interior of the unit.

Figure 4: Interior of the IKEA "Better Shelter"

Despite its award-winning credentials, the Better Shelter design received criticism earlier this year over concerns regarding the structure's vulnerability to fire. These concerns have led the United Nations High Commission for Refugees (UNHCR) to deploy just 5,000 of the 15,000 units produced thus far (Fairs, 2017). Additionally, while the Better Shelter is a quick and affordable design for refugee applications, it is not intended as a standalone unit. It can only be used as part of a larger complex with multiple units and separate shared kitchen and bathroom facilities. Like the CFU, the Better Shelter also does not include internal features such as furniture, which must be stored and shipped separately.

3.2 Temporary Housing Design Parameters

The unit designed in this project are intended for use in areas susceptible to hurricanes. Though hurricanes affect many areas, this project employs climate data from Miami-Dade County, Florida, which has a climate representative of many areas most affected by hurricanes. Miami-Dade County also has a high population density, meaning it would likely have a significant need for temporary housing in the event of a severe hurricane. Because the temporary housing units can be used at any time, they must be able to survive in any season.

3.2.1 Temperature

For Miami-Dade County, the record high and low temperatures are 100°F (37.8°C) and 27°F (-2.8°C), respectively (Climatological Records of Miami, FL). Average temperatures vary by month, but the average annual temperature is 77.5°F (25.3°C). By month, January has the coldest average low temperature at 60.0°F (15.6°C). July and August have the warmest average high temperature at 91.0°F (32.8°C) (World Weather and Climate Information).

3.2.2 Rainfall and Flooding

To determine which parts of Miami-Dade Country are most at risk of high water events, flood zone maps detail the probability, predicted depth of floodwaters, and insurance requirements. The flood zone with the highest insurance requirement is known as Zone AH and is shown in purple in Figure 5.

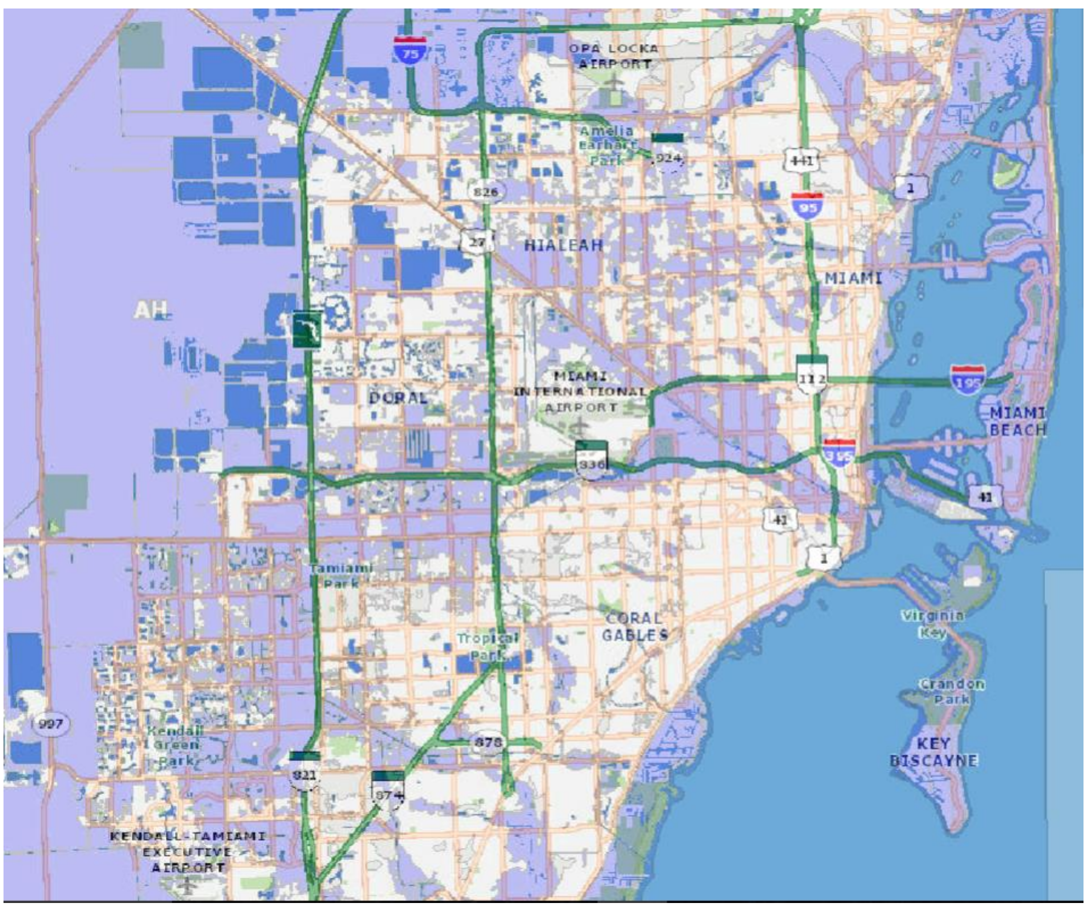


Figure 5: Miami-Dade Country Flood Zones, with Zone AH shown in purple (Flood zones)

Zone AH corresponds with a 100-year flood that causes 1 ft to 3 ft (0.3 m to 0.9 m) of floodwater depth. This means that there is a 99% chance that floodwaters will stay below 1 ft (0.3 m) in any given year (Miami-Dade Country Flood Zone Maps). There is an average of 128 days of precipitation per year, which accounts for an average precipitation of 61.93 in. (157.3 cm) per year. During the rainiest months, May to October, there is an average rainfall of 14.83 days per month (US Climate Data).

3.2.3 Humidity

The annual average humidity percentage in Miami Dade County is 72%. The muggier periods of the year last for 7.9 months, from April to December. This is important to note as high levels of humidity can create dissatisfying living conditions. For comfortable living. The humidity inside a housing unit will need to be around 50% (CLIMAT, 2017).

3.2.4 Wind

In areas that often experience high winds, special consideration is given to the design of structures. Envelope damage, structural damage, and missile damage are the three main concerns during construction. Envelope damage affects the part of the unit that separates indoors and outdoors. Structural damage affects the inner support system. Missile damage is wind-borne debris striking the side of the structure, potentially puncturing the envelope and creating the potential for more significant damage (Making Critical Facilities Safe from High Winds). Sustained winds in Miami reach up to 69 mph (31 m/s) and gusts reach nearly 100 mph (45 m/s). During a Category 5 hurricane, sustained winds are at least 155 mph (69 m/s) with gusts over 189 mph (84 m/s). (Florida Climate Center) The American Society of Civil Engineers Standard requires that buildings are designed to withstand wind speeds of 146 mph (65.27 m/s) in Miami-Dade County (The Florida Building Code).

3.2.5 Consumer Parameters

When a family loses their home, the effects can be traumatic both economically and mentally. The National Institute of Mental Health studied two communities that were dispersed due to natural disasters. Measurements were taken at two points in time and it was found that, "levels of short-term stress symptomatology and diagnosable PTSD were substantial in both communities" (Steinglass, 1990). Based on this research, a temporary housing unit must be comfortable to reduce stress and emotionally aid in the rebuild process (Caia, 2010).

To provide comfortable living conditions, the temporary housing unit must contain the amenities of a normal home and preserve privacy (Rich Stapleton, personal communication, September 21, 2017)**.** The size, scale or extent of each amenity can differ, but each unit must include a toilet, a shower, a sink, a food preparation area, a sleeping area, and a common living space. These features should be laid out to provide adequate privacy to the occupants (Rich Stapleton, personal communication, September 21, 2017). Ideally, wall, floor, and ceiling aesthetics will resemble those of permanent housing structures.

There are also specific building codes in place to ensure occupants have adequate living space. For example, a temporary housing unit must provide easy access to fire extinguishers, with one means of escape in an emergency situation. Additionally, there should be a minimum of one window, a minimum door width of 32 in (81 cm), a minimum ceiling height of 7 ft (2.1 m), and 40 ft^2 (3.7 m^2) of floor space per person residing in the unit. However, since the unit is temporary, it is not required to comply with the typical housing codes and requirements. For example, the unit does not need to include special accommodations for people with disabilities, nor must it follow typical egress protocol (FEMA 453, 2006). Due to its compact structure, this design is not likely to be a solution for handicapped victims; FEMA will continue to rely on current methods to provide housing for such victims.

3.2.6 Materials

The materials used to construct a temporary housing unit have a significant effect on the structure, difficulty of the assembly process and the life cycle of the product. The chosen material needs to give structural support to the unit, withstand weather conditions, and prevent corrosion, mold and out-gassing. The unit should have a lifespan of at least 20 years and withstand repeated use (Rich Stapleton, personal communication, November 7, 2017).

3.2.7 Transportation and Assembly

A housing unit cannot be used effectively if it cannot be easily moved from storage to the impacted location. Temporary housing units can be transported via road or sea. When traveling via road, the dimensions and weights of the unit must comply with trucking requirements. United States requirements limit a standard trailer load to dimensions of 8.5 ft (2.6 m) height, 53 ft (16.2 m) length, and 8 ft (2.4 m) width, and a weight of 36,000 lb (16,000 kg) (Federal, 2004). When traveling by sea, the unit must be stackable and able to interact with a crane.

A common challenge with temporary housing units is the time and effort needed to fully erect the unit. Upon arrival, unit assembly time should be minimized. The unit should be able to be assembled by workers and hand tools, without any heavy machinery such as fork lifts (Rich Stapleton, personal communication, November 7, 2017).

Chapter 4: Concept Development

4.1 Generation of Design Parameters and Specifications

To better understand needs, current solutions' drawbacks, desired improvements, and preferable attributes, the team interviewed employees of Deployed Resources. Combining input from these conversations with other background research, the team developed design parameters. The design parameters were a set of features and characteristics to be included in the temporary housing unit. These parameters can be seen in Table 1.

Table 1: Design Parameters and Descriptions

Parameter	Description
The unit should withstand the environment	• The unit must withstand expected temperatures and weather conditions • There should be no water leaking into the unit • The unit should withstand wind loading
The unit should fit at least four people	• A family of four should be able to live in the unit
The unit should include a bathroom	• The bathroom should include a toilet and shower • The bathroom should be private from the rest of the space
The unit should include a kitchen	• The kitchen should include a sink, countertop space, shelving, and a mini fridge
The unit should have climate control	• The unit should be equipped with an AC/heating unit to maintain a comfortable living temperature
The unit should have electricity	• The unit should be able to connect to a power source • The unit should be equipped with a power panel and wiring system
The unit should have clean water	• The unit should be able to connect to a water source
The unit should be partially collapsible	• The unit should collapse but still be able to store the bathroom, kitchen, and other supplies in it • Multiple collapsed units should be able to fit onto a trailer bed • The unit should save storage space

The unit should stand above the ground and be able to level	• The unit should be at a height above the ground for air circulation and to reduce flooding risks • The unit should adjust to the ground it is being set up on
The unit should be modular	• The unit should be able to attach to other units for a larger space
The unit should have a fast and easy set-up	• The unit should be able to be set up without large machinery (i.e. forklift) • The unit should not take more than a few hours to set up
The unit should have a low manufacturing cost	• The unit should not exceed $15,000 to manufacture
The unit should have a low manufacturing time	• The unit should be fast to manufacture
The unit should be reusable	• The unit should be able to serve multiple disaster relief responses • The unit should be able to withstand storing conditions • There should be no molding, rusting or outgassing • The unit should be easily sanitized after use
The unit should be easy to transport	• The unit should be light weight • The collapsed unit should be able to be moved by a forklift
The unit should be safe and secure	• The unit should incorporate a locking system, fire extinguishers, etc.
The unit should have a waste management system	• The unit should have a sanitary way to dispose of waste
The unit should be furnished	• The unit should have amenities included such as beds, couches, table, chairs, etc.
The unit should incorporate renewable energy	• The unit should be able to be equipped with a solar panel

After the parameters were established, they were given weights based on the categories listed below:

- 10 - Required for product to be usable; the team must create a unique design
- 8 - Highly recommended for product to be usable; the team must create a unique design
- 6 - Highly recommended for product to be usable; could use existing design or have sponsor create design
- 4 - Usable product may not have this; could use existing design or have sponsor create design
- 2 - Desired feature but not critical to design

This scoring system allowed the team to determine the most important requirements to focus on in the design of the temporary housing unit. In order to make the design parameters measurable, the team created specifications using the data provided in the Background chapter of the report. These specifications were used to design a temporary housing unit that would comply with relevant building codes, withstand environmental conditions, and be transportable to various locations. Table 2 shows the weight and specification associated with the various parameters.

Table 2: Design Parameter Weights and Specifications

Parameter	Weight	Specification
The unit should withstand the environment	10	The unit must be able to withstand up to 146 mph (65 m/s) wind speeds
The unit should include a bathroom	10	The unit should include a toilet and shower
The unit should include a kitchen	10	The unit should include a sink, refrigerator, hot plate and counter space
The unit should stand above the ground and be able to level	10	The unit should stand a minimum of 1 ft (0.3 m) above the ground
The unit should have a low manufacturing cost	10	The unit should not exceed a manufacturing cost of $15,000
The unit should fit at least four people	8	The expanded unit must provide a minimum of 160 ft^2 (14.9 m^2) of livable space The unit must have a minimum ceiling height of 7 ft (2.1 m) The unit must include one 32-in. (0.8-m) wide door for entry and egress
The unit should be partially collapsible	8	A minimum of 2 collapsed units must fit onto a trailer
The unit should be modular	8	The unit should be able to be attached to at least one other unit to create a larger unit
The unit should have a fast and easy set-up	8	On-site set up should take less than 4 hours and should not require specialized tools
The unit should be reusable	8	The unit should withstand at least 3 cycles of use and storage
The unit should be easy to transport	8	The unit weight and geometry should allow for use of a forklift
The unit should have climate control	6	The unit must maintain an inside temperature between 60-80°F (16-27°C) and a 40-50% humidity level when in use
The unit should have electricity	6	The unit should include a connection to a local power source, or provide equivalent power
The unit should have clean water	6	The unit should include a connection to a local water source
The unit should be safe and secure	6	The unit should include a locking system and one fire extinguisher
The unit should have a waste management system	6	The unit should produce no pollution to the environment

The unit should have a low manufacturing time	4	Each unit should not take longer than 2 months to manufacture
The unit should incorporate renewable energy	4	At least 50% of the energy consumed by the unit should be supplied by renewable energy (solar or wind)
The unit should be furnished	2	The unit should include one bed, one couch, and one table with chairs

4.2 Design Concept Generation and Selection

4.2.1 Initial Design Concepts

With the design parameters and specifications in Table 2 in mind, the team started generating ideas and concepts to address the need for a collapsible disaster relief structure. Some of the most successful preliminary designs are discussed below.

The Folding Design was a unit that incorporated a main compartment which would remain permanent, with folded wall portions on the side to be expanded. The floors would first fold down, the ceiling would fold up, and the walls would follow to slide out. This folding technique would be incorporated on the two long sides of the permanent portion of the unit. This design can be seen in Figure 6.

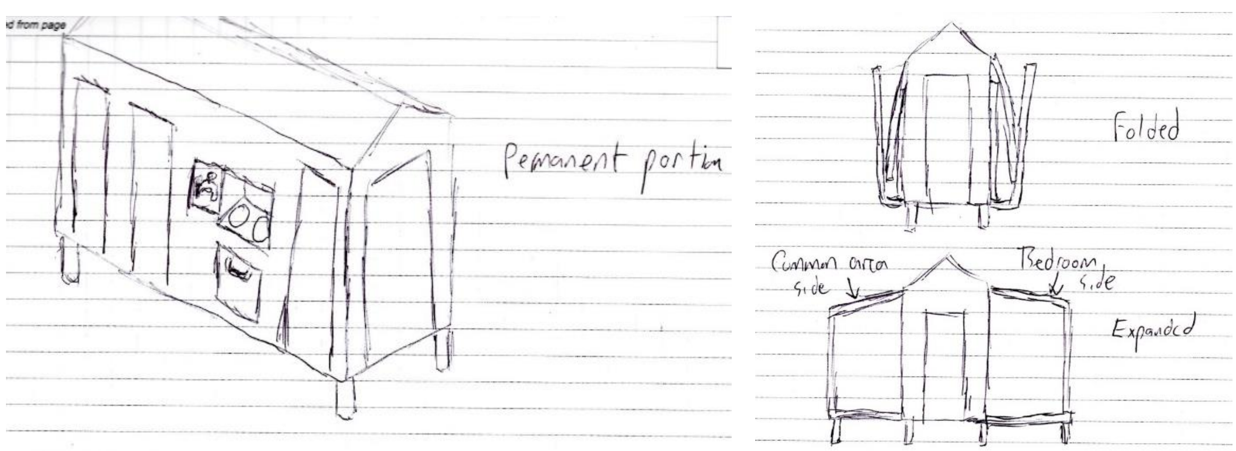


Figure 6: The Folding Design Expanded

The Accordion Design was a unit in which the walls and roof would fold in and out in the shape of an accordion. The roof would be arched and connected with the wall portion of the structure. These walls would be mounted to a track on the floor and would slide up to a permanent, rigid body compartment containing internal appliances. Then, the floor would fold up to close the collapsed unit. This design can be seen in Figure 7.

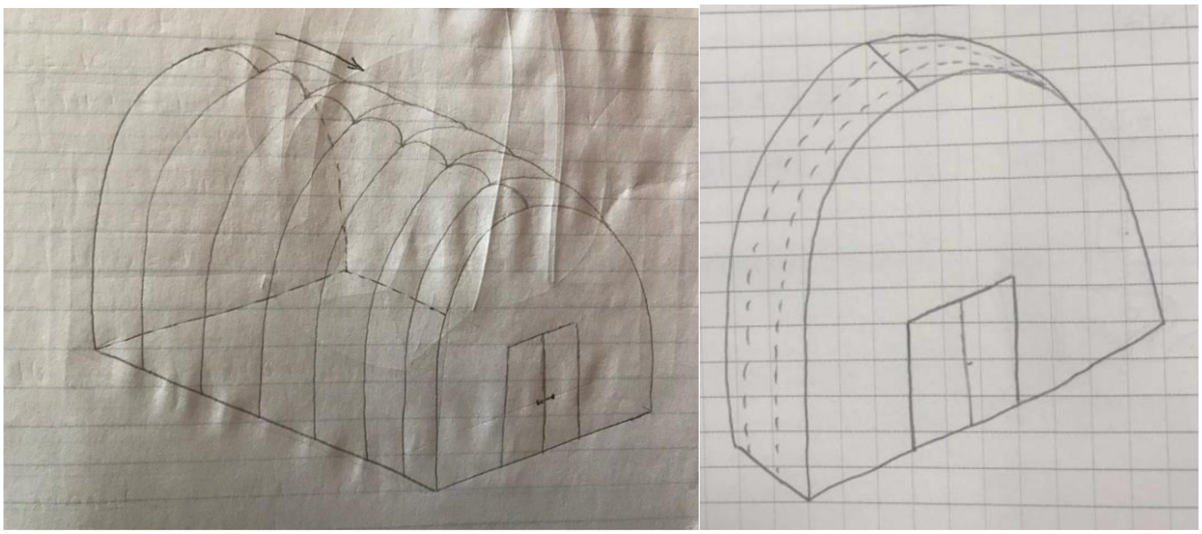


Figure 7: The Accordion Design, expanded (left) and collapsed (right)

The Drawer Design incorporated a permanent compartment that would house another smaller compartment within it, which would slide out and expand the size of the unit. The floor, walls, and roof of the smaller compartment would already be joined to make the expansion of the unit faster and easier, requiring a single pull. The walls would have tracks on the side to connect the sliding and permanent compartments, similar to a drawer mechanism. This design can be seen in Figure 8.

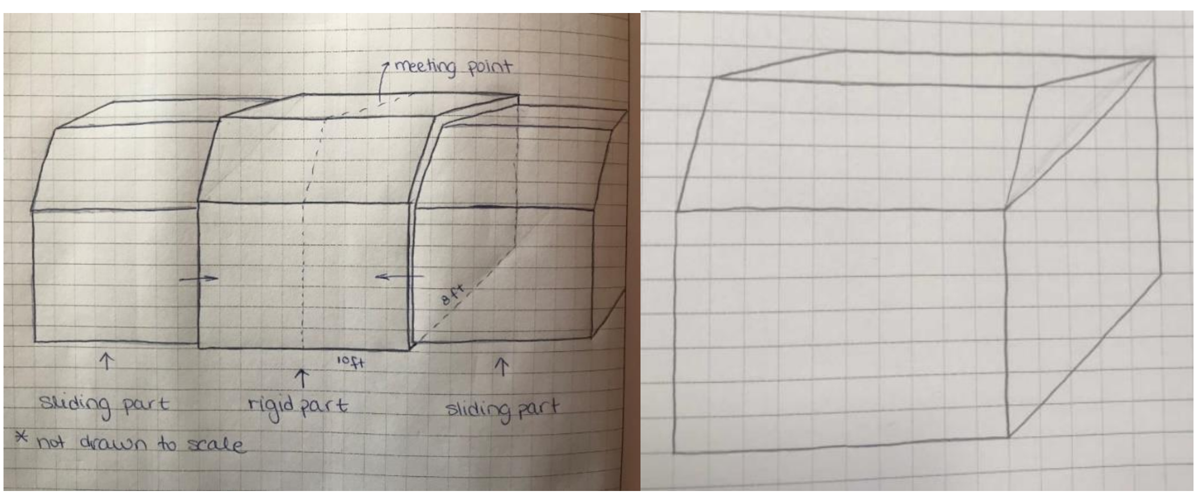


Figure 8: The Drawer Design, expanded (left) and collapsed (right)

The "Bug Net" Design was a unit in which the center point of each wall would be pulled into the structure and meet in the middle, resembling a bug net tent. These walls would then fold down to the floor to create a flat surface. The roof portion of the unit would also collapse down on top of the walls and the floor. See Figure 9 for a visual of this design.

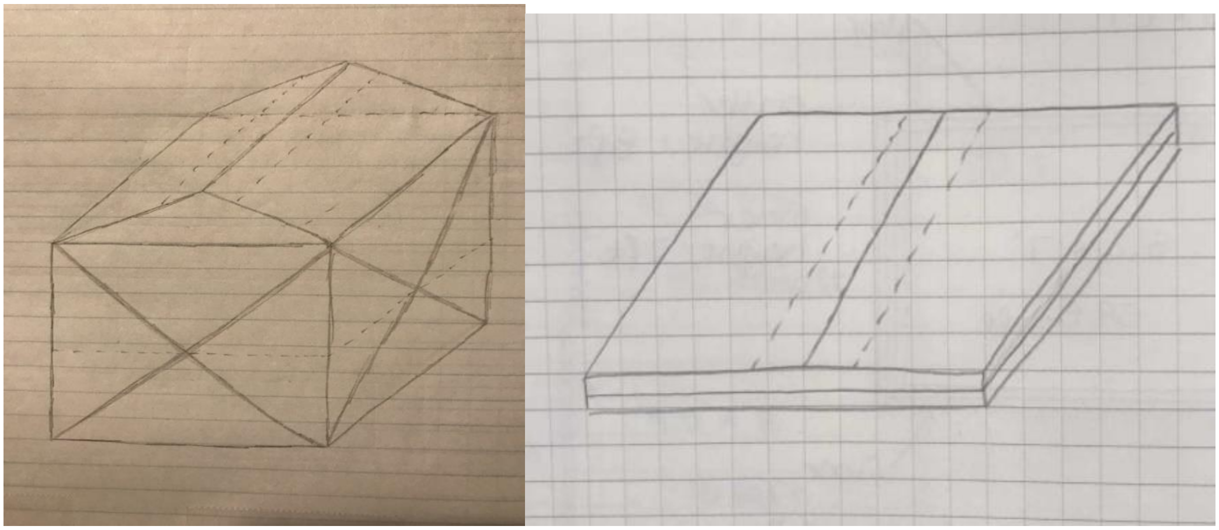


Figure 9: The "Bug Net" Design, expanded (left) and collapsed (right)

The Origami Design was a fixed frame design that would lay flat when collapsed and then rotate up into a dome shape. The curved studs would have fold-out members that would attach to each other creating a pattern of truss structures. The framed structure would then be covered with a flexible tear-resistant fabric to offer privacy and protection from the elements. This design can be seen in Figure 10.

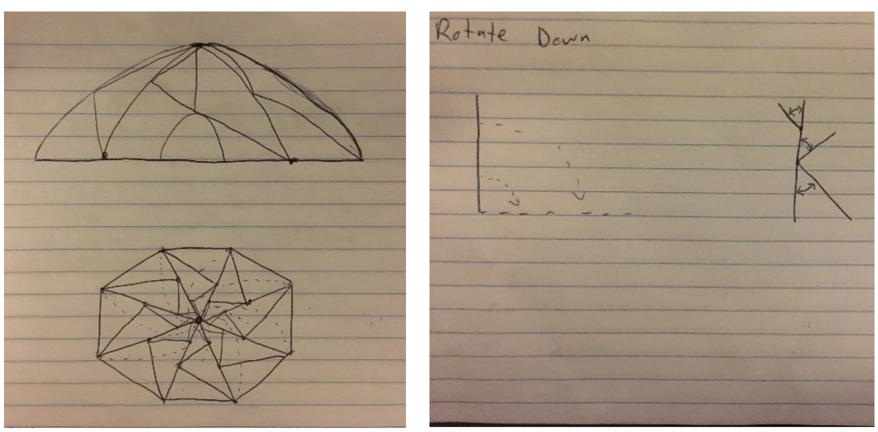


Figure 10: The Origami Design

The Tube Design consisted of a self-contained column that held internal appliances and a tent that expanded out to create living space. The tent poles would be extended using a ratchet system and a flexible sheet would cover them, similar to an umbrella. This design can be seen in Figure 11.

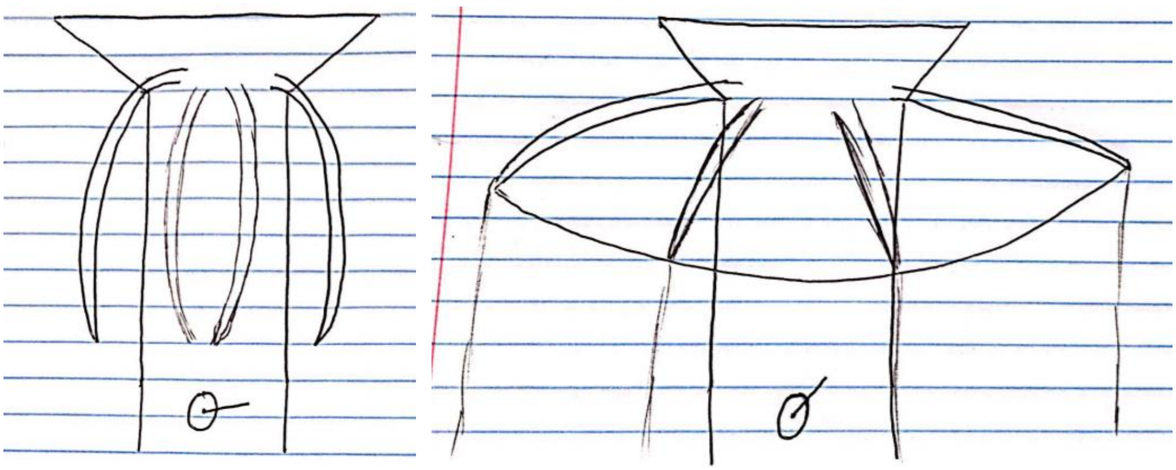


Figure 11: The Tube Design

4.2.2 Design Selection

Of the six designs described in Section 4.2.1, three designs were determined to be non-viable solutions.

The Bug Net Design was eliminated from consideration due to the high number of gaps created by the complex wall design. These gaps would require very tight tolerances when manufacturing the wall components to ensure the structure is completely sealed from the exterior when expanded. The Bug Net design is also a fully collapsible design and does not have the ability to function as a partially collapsible design with certain interior components built in.

The Origami Design was also eliminated from consideration due to the unique structural elements required. The curved studs would require significant time and cost to both design and manufacture, meaning the design would likely exceed the target budget. Additionally, like the Bug Net design, the Origami design functions only as a fully collapsible design rather than a partially collapsible design.

Lastly, the Tube Design was eliminated from consideration over concerns regarding structural stability. While the design provides a partially collapsible concept that is relatively lightweight, it proved difficult to incorporate structural members capable of withstanding hurricane-force winds into a ratchet system. Such a system, covered only by a flexible sheet, was deemed insufficient for extended-term use.

The Drawer Design, Folding Design and Accordion Design were identified as the three most viable solutions. Each of these three concepts was compared using a decision matrix to evaluate the parameters, specifications, and weights identified in Section 4.1. For each parameter, the designs were given a rating of 1-3. Designs that least effectively met a specification received a 1, and designs that most effectively met a specification received a 3. These scores were multiplied by the parameter weight assigned in Section 4.1. The Drawer Design received the highest score, followed by the Folding Design and the Accordion Design. Table 3 presents the decision matrix used to select a final concept.

Table 3: Decision Matrix - Design Selection

		Drawer Design		Folding Design		Accordion Design	
Parameter	Weight	Un-weighed	Weighed	Un-weighed	Weighed	Un-weighed	Weighed
The unit should withstand the environment	10	3	30	2	20	1	10
The unit should include a bathroom	10	3	30	1	10	2	20
The unit should include a kitchen	10	3	30	1	10	2	20
The unit should stand above the ground and be able to level	10	1	10	2	20	3	30
The unit should have a low manufacturing cost	10	3	30	2	20	1	10
The unit should fit at least four people	8	1	8	3	24	2	16
The unit should be partially collapsible	8	2	16	1	8	3	24
The unit should be modular	8	1	8	3	24	2	16
The unit should have a fast and easy set-up	8	3	24	1	8	2	16
The unit should be reusable	8	2	16	3	24	1	8
The unit should be easy to transport	8	3	24	2	16	1	8
The unit should have climate control	6	1	6	3	18	2	12
The unit should have a low manufacturing time	4	3	12	2	8	1	4
The unit should be furnished	2	3	6	2	4	1	2
Total			250		214		196

4.2.3 Further Development of Drawer Design

The original Drawer Design consists of a main compartment out of which a smaller compartment slides out. The design requires a track system that allow smooth motion of the sliding compartment and seals the unit from the external environment. The main issue with the Drawer Design was the large moment exerted on the joints due to the cantilevered section sliding out of the main compartment.

To eliminate this shortcoming, the team combined elements of the Folding Design and the Drawer Design. The result was a semi-collapsible unit in which a panel acted as a wall in the closed position, then folded down into a floor in the open position. Leveling feet were attached to the fold-down floor to provide additional supports at a distance away from the main compartment, preventing a cantilevered system. Figure 12 shows the original sketches of the combined design idea, and Figure 13 highlights the role of the leveling feet.

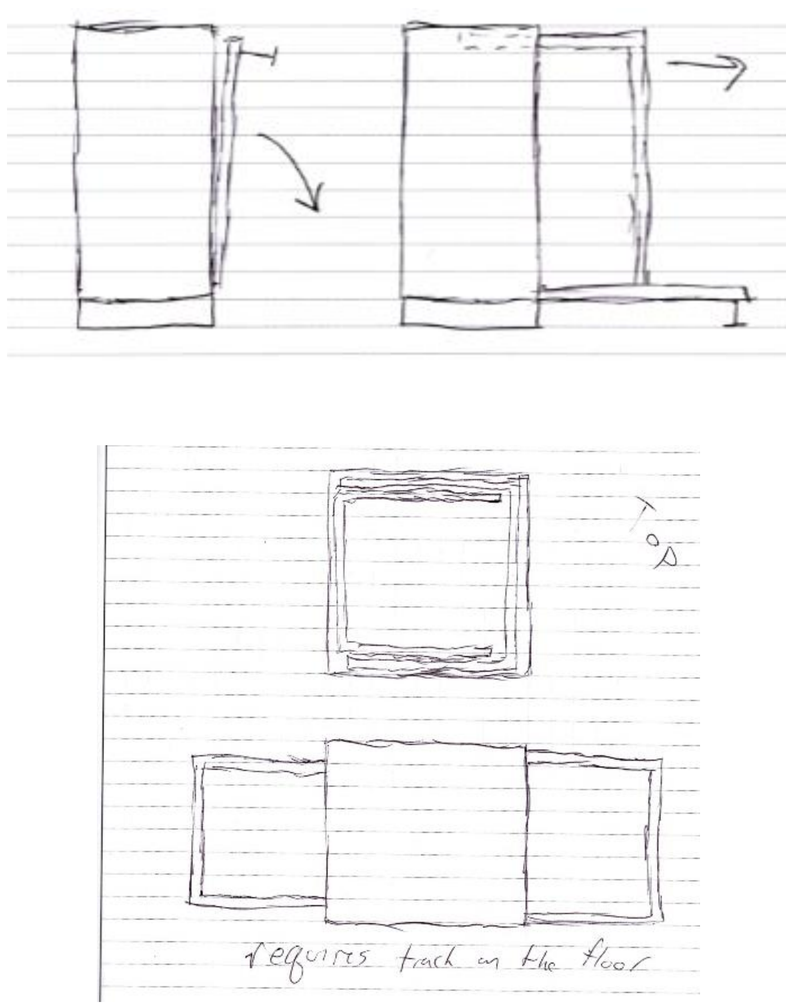


Figure 12: Original Sketches of Final Design

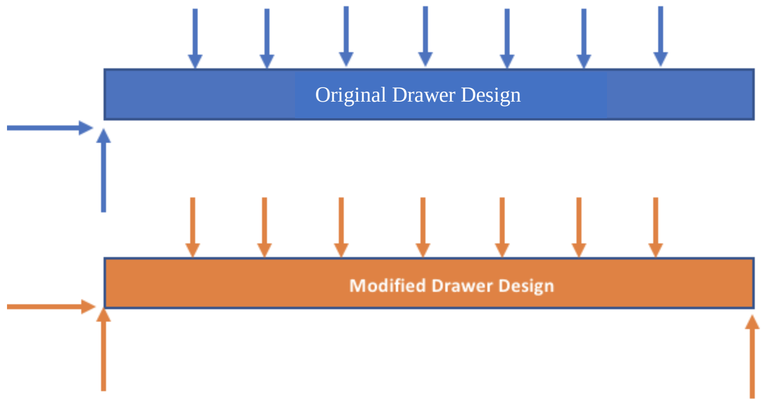


Figure 13: Comparison of Typical and Modified Drawer Design

A benefit of this modification was that living amenities could now be permanently stored within the structure. Nesting the floor of the sliding compartment within the main compartment along with the walls and roof would obstruct the main compartment floor when the unit is in the collapsed position. Any mounted permanent appliances would need to be attached to the sliding compartment. This was not an ideal design, as the team preferred to connect these appliances to the main compartment where they could remain stationary and help center the weight distribution of the unit. With the floors of the sliding compartment now folding down from the wall, the main compartment would be exposed even in the collapsed position, allowing for the mounting of appliances to that surface.

The team developed 4 different concepts for the expansion. The first concept was one section (dotted lines) sliding out of a main compartment (solid lines) in one direction. (see Figure 14)

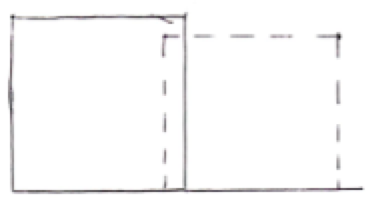


Figure 14: Sliding Expansion Concept 1

The second concept was two sections expanding in one direction. (see Figure 15)

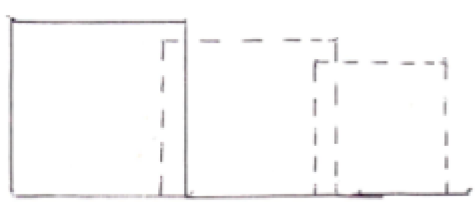


Figure 15: Sliding Expansion Concept 2

The third and fourth concepts were similar, with two separate sections sliding out in opposite directions. The third concept involved two sliding sections that were half the size of the main compartment, meeting in the middle of the main compartment (see Figure 16 and Figure 17).

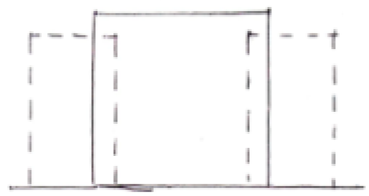


Figure 16: Sliding Expansion Concept 3

The fourth concept nested the two expandable sections within each other inside of the main compartment. This allowed the expandable sections to be larger than half the size off the main compartment.

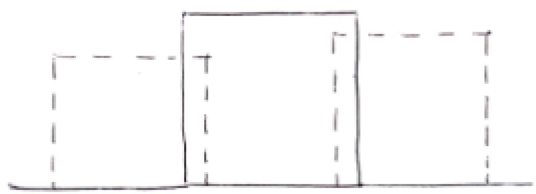


Figure 17: Sliding Expansion Concept 4

To visualize these concepts, the team built 1:4 scale wooden prototypes as shown in Figure 18. Appropriate safety precautions were taken, including utilizing personal protective equipment (PPE) and the Advanced User Training at the WPI on-campus manufacturing facility. During construction, the team searched for design and manufacturing issues that were either present in the scale model or could be foreseen to propagate in the full-scale model. This process revealed which concepts were viable in practice, and which concepts had flaws too great to overcome.

Figure 18: Construction of 1:4 scale wooden prototypes

To select one concept, the team used a decision matrix which evaluated each of the four concepts based on maximum expanded size, minimum contracted size, ease of use, and ease of manufacture. Ease of use describes the efforts needed to set up the unit once it is on site, while ease of manufacture describes the efforts required to construct the unit. Table 5 gives descriptions of the parameters used. For each parameter, the designs were compared and given a rating of 1-4. Designs that least effectively met a specification received a 1, and designs that most effectively met a specification received a 4. The team selected sliding expansion Concept 4 based on the decision matrix in Table 4.

Table 4: Decision Matrix - Expansion Concept

Parameter	Weight (0-10)	Concept 1		Concept 2		Concept 3		Concept 4	
		Un-Weighted	Weighted	Un-Weighted	Weighted	Un-Weighted	Weighted	Un-Weighted	Weighted
Max. Expand	10	1	10	3	30	2	20	4	40
Ease of Set up	8	4	32	3	24	2	16	1	8
Ease of Manufacture	6	4	24	2	12	1	6	3	18
Stability	6	2	12	1	6	4	24	3	18
FINAL SCORE			**78**		**72**		**66**		**84**

Table 5: Expansion Concept Selection Parameters

Parameter	Description
Max Expand	Which unit expands to the largest internal area
Ease of Setup	The effort, equipment, and time required to set up the unit from the collapsed to expanded position
Ease of Manufacture	The effort, equipment, and time required to assemble the unit
Easy and quick set-up	Level of difficulty required to set up the system on site, based on tools and number of people required
Stability	How evenly the mass of the structure is distributed across the unit footprint

Chapter 5: Final Design Optimization

5.1 Failure Modes and Effects Analysis (FMEA)

To identify possible design flaws, the team conducted a Failure Modes and Effects Analysis (FMEA). This analysis identifies potential failure modes by ranking both severity and occurrence on a scale of one (unlikely to cause harm/unlikely to occur) to four (catastrophic/likely to occur). The product of the two scores provides a hazard score. A hazard score between one and four means the failure mode is a low risk and does not need to be addressed. Any score above a four needs to be addressed, and any score above an eight needs to be addressed with high urgency. Potential failure modes associated with the design were assessed and given hazard scores. This analysis identified the most important aspects of the design which needed further development to mitigate risk. Table 6 shows critical results from the FMEA. The analysis identified the wheels and track system, the leveling system, and the resistance of the structure to wind loading as the greatest hazards in the design. Section 5.2 will describe the design choices made to mitigate these risks. Appendix A contains the full results of the FMEA.

Table 6: FMEA critical results

Function/Process	Potential Failure Mode	Potential Effect of Faliure	Severity (1-4)	Potential Cause of Faliure	Occurrence (1-4)	Hazard Score
Track system	Sliding walls get knocked off the track	housing unit will be compromised, lives are at risk	4	Unexpected force on walls, track is not straight	3	12
Feet and leveling system	Feet buckle under weight and break	floor is damaged	4	too much weight is put on the feet	2	8
Structure	Unit tips over in expanded	Housing unit destroyed, loss of life	4	wind force is greater than COM force	2	8

5.2 Structural Design Decisions & Details

After selecting the partially-collapsible, drawer-style design for further development, the team made decisions regarding the dimensions and materials selection, the internal floor plan layout, and the building systems to be incorporated. These choices were driven by the same design parameters used to evaluate the overall candidate designs. Decision matrices were also used to determine the best available option among different design ideas.

5.2.1 Sizing and Dimensions

To determine an effective and achievable unit size, the team addressed maximum exterior dimensions, maximum allowable weight, and required internal square footage for habitable space. The maximum exterior dimensions and weight were restricted by shipping standards. In the United States, each truck load is limited to dimensions of 8.5 ft (2.6 m) height, 53 ft (16.2 m) length, and 8 ft (2.4 m) width, and a weight of 36,000 lb (16,000 kg) (Federal, 2004). Figure 19 shows these standard dimensions.

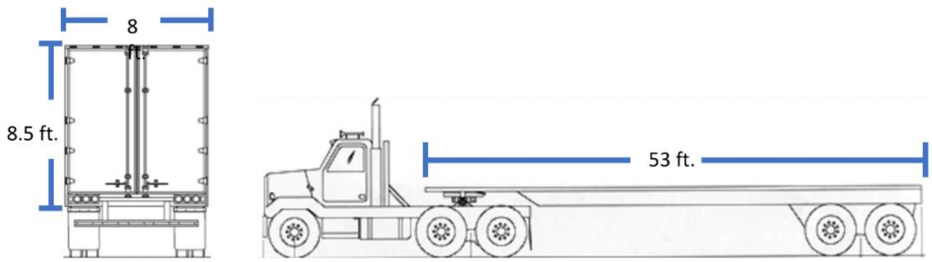


Figure 19: Standard United States shipping dimensions

The structures were designed to ensure that five units could be shipped on a single truck. Based on shipping constraints, the team pursued a design with collapsible external dimensions limited to 8.5 ft (2.6 m) height, 10.6 ft (3.2 m) length, and 8 ft (2.4 m) width, and a weight not exceeding 7,200 lb (3270 kg).

The interior dimensions were driven by Section 1.7.1.2 of FEMA 453, *Safe Rooms and Shelters*, which requires a minimum of 40 ft^2 (3.7 m^2) of floor space per occupant in temporary shelters that are used for more than a few days. The internal dimension parameter is evaluated based on the number of allowable occupants for the available floor area. The chosen design resulted in approximately 200 ft^2 (18.6 m^2) of floor space, meaning the unit has a capacity of up to five occupants.

5.2.2 Roof

Three different roofing materials were evaluated for the design. The first option was SUNTUF corrugated polycarbonate sheets. These sheets are primarily used in greenhouse, covered patio and outdoor storage applications rather than for residential units. They are attractive because of their lightweight design. The panels, however, are expensive and are not designed to provide a residential unit with adequate protection from wind and rain. They would require an additional layer of insulation as they do not provide significant insulation on their own. Figure 20 shows SUNTUF panels installed as part of a covered outdoor storage area.

Figure 20: SUNTUF roofing panels

Next, simple corrugated steel roof panels were evaluated. This material would minimize cost, could be purchased quickly and easily, and would involve a simple set-up process. Like SUNTUF panels, however, corrugated steel does not provide significant insulation. Installing these panels would require an additional manufacturing step to properly insulate the roof for both temperature control and noise reduction. This steel roof and insulation assembly would present the risk of condensation build up. Figure 21 shows a cabin with a corrugated steel roof.

Figure 21: Corrugated steel roofing

The third roofing option was PermaTherm insulated metal roofing panels. These panels consist of a 3-in. (7.6-cm) layer of expanded polystyrene (EPS) reinforced by a sheet of 26-gauge galvanized steel on each side. The EPS provides an insulation R-value of 12.75, while the sheet metal finish has a yield strength of 250 MPa, reinforcing the panels to withstand impact forces. PermaTherm roof panels cost $4.66/ft^2 and include necessary framing and fasteners, streamlining the set-up process. Figure 22 shows a roof partially equipped with PermaTherm panels.

Figure 22: PermaTherm roofing panels

Table 7 below summarizes values pertinent to the roofing material selection.

Table 7: Roofing Material Properties and Values

Product	Weight (lb/sqft)	Cost (per sqft)	Yield Strength (MPa)	Insulation (R-value)
SUNTUF	0.20	> $4.66	62	0.04
corrugated steel	0.73	$0.95	250	7.20E-06
PermaTherm	2.60	$4.66	250	12.75

As a result of the decision matrix in Table 8, the team selected PermaTherm insulated metal roofing panels for use in the design. Descriptions of each parameter are provided in Table 9.

Table 8: Decision Matrix - Roofing Material

Requirements	Weight (0-10)	SUNTUF Un-weighted (1-3)	SUNTUF Weighted	Corrugated Steel Un-weighted (1-3)	Corrugated Steel Weighted	PermaTherm Un-weighted (1-3)	PermaTherm Weighted
Withstands the environment	10	1	10	2	20	3	30
Cost	10	1	10	3	30	2	20
Easy to transport (weight/size)	8	3	24	2	16	1	8
Easy and quick set-up	8	2	16	1	8	3	24
Climate control/insulation (AC, heating)	6	2	12	1	6	3	18
Low manufacturing time	4	1	4	3	12	2	8
FINAL SCORE		10	**76**	12	**92**	14	**108**

Table 9: Roof Material Selection Parameters

Parameter	Description
Withstands the environment	Expected lifespan of the system structure under expected loading and fatigue
Cost	Total cost of the system
Easy to transport (weight/size)	Level of difficulty required to move the system both long and short distances, based on size, shape, and weight
Easy and quick set-up	Level of difficulty required to set up the system on site, based on tools and number of people required
Climate control/insulation (AC, heating)	Insulation rating of the system
Low manufacturing time	Time required to purchase parts and manufacture the system

5.2.3 Walls

The team also explored three wall materials as primary options for the design. The first material considered was the wall system previously used by Deployed Resources for its products formed from shipping containers. This system consists of FiberCorr, a fiberglass-reinforced plastic (FRP) panel that is lightweight and moisture resistant, as well as P2000, an EPS insulating panel. The FiberCorr is used as the interior finish and mounted to studs. The P2000 is mounted to the other side of the stud and finished with another layer of FiberCorr. This design is attractive due to its strong insulation capabilities, and because of Deployed Resources' familiarity with the design. But the FiberCorr/P2000 wall system also requires the use of studs, which add both weight and thickness to the walls. Additionally, the FiberCorr itself is not rated as an exterior finish, so the design would also require an additional layer of impact-resistant material. A cross-sectional side view of this design for the collapsed unit is shown in Figure 23.

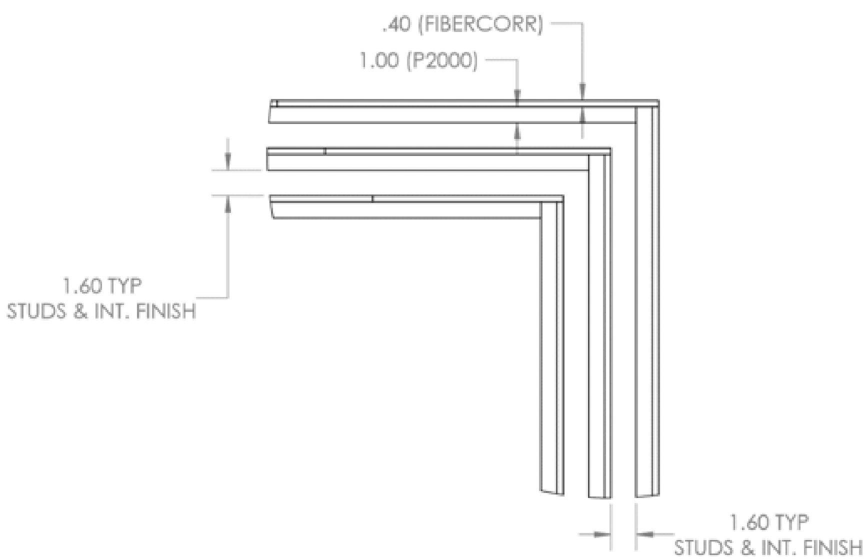


Figure 23: Fibercorr/P2000 studded wall configuration

In an effort to minimize the wall thickness and maximize internal dimensions of the unit, the team next explored Endurex 555, a high-impact hurricane panel manufactured by Nudo. The panels are approximately 1 in. (25 mm) thick and are mounted into aluminum U-channels, so they do not require studs. With this design the total wall thickness could be reduced to 1.5 in. (38 mm) or less. The Endurex 555 panels, however, cost about $\$14/ft^2$, resulting in a total cost of over $8,000 for the walls of a single unit. They would require special installation which would increase labor and material cost. The R-value of 4.8 for these panels was the lowest insulation rating of the three options considered. Also, the panels are typically mounted into window glazing to provide impact resistance, but not necessarily structural stability. Based on installation guidelines, using Endurex 555 to construct an entire wall would not provide adequate stability to the unit. Figure 24 shows a cross-section view of an Endurex 555 panel and an example of how the panels are installed into aluminum U-channels.

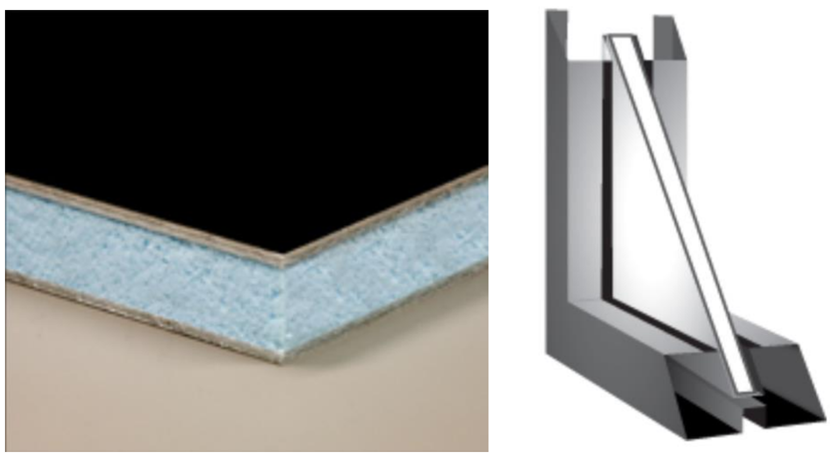


Figure 24: Endurex 555 wall panels

PermaTherm insulated metal panels were the third option explored for the wall material. These panels are very similar to the PermaTherm roofing panels discussed in Section 5.2.2. They consist of a 3-in. (7.6-cm) thick layer of EPS insulation with 26-gauge galvanized steel finish on each side. The panels are 46 in. (1.2 m) wide and cut to length, and they fit together using a tongue-and-groove system. These characteristics reduce the required set-up time. While the panels are thicker than Endurex 555, they provide more insulation and structural stability at less cost. Figure 25 shows PermaTherm wall panels used for a temporary office unit.

Figure 25: PermaTherm wall panels

Table 10 below summarizes values pertinent to the wall material selection.

Table 10: Wall Material Properties and Values

Product	Weight (lb/sqft)	Cost (per sqft)	Thickness (in.)	Insulation (R-value)
FiberCorr/P2000	1.56	$3.50	3.5	10.2
Endurex	1.58	$14.00	< 1.5	4.8
PermaTherm	2.60	$4.66	3.0	12.75

The team used the decision matrix in Table 11 to select PermaTherm insulated metal panels for use in the design. Descriptions of each parameter are provided in Table 12.

Table 11: Decision Matrix - Wall Material

Requirements	Weight (0-10)	FiberCorr/P2000 Un-weighted (1-3)	FiberCorr/P2000 Weighted	Endurex Un-weighted (1-3)	Endurex Weighted	Perma Therm Un-weighted (1-3)	Perma Therm Weighted
Withstands the environment	10	3	30	1	10	2	20
Cost	10	3	30	1	10	2	20
Easy to transport (weight/size)	8	3	24	1	8	2	16
Easy and quick set-up	8	1	8	2	16	3	24
Climate control/insulation (AC, heating)	6	2	12	1	6	3	18
Low manufacturing time	4	1	4	2	8	3	12
FINAL SCORE		13	**108**	8	**58**	15	**110**

Table 12: Wall Material Selection Parameters

Parameter	Description
Withstands the environment	Expected lifespan of the system structure under expected loading and fatigue
Cost	Total cost of the system
Easy to transport (weight/size)	Level of difficulty required to move the system both long and short distances, based on size, shape, and weight
Easy and quick set-up	Level of difficulty required to set up the system on site, based on tools and number of people required
Climate control/insulation (AC, heating)	Insulation rating of the system
Low manufacturing time	Time required to purchase parts and manufacture the system

5.2.4 Floor

The team explored three floor materials as primary candidates for the design. The first material considered was a simple plywood design, as is used in many permanent homes. Because these units will be stored in unconditioned climates for long periods of time when not in use, plywood raised concerns about mold resistance and ultimately the longevity of the unit. Deployed Resources also advised against using plywood based on previous issues in similar applications.

The team then explored the use of NuPoly QuadFloor, a product of Nudo, the same company that manufactures the Endurex 555 wall panels discussed in Section 5.2.3. This product consists of oriented strand board (OSB) overlaid with plywood on both sides and then a thin high-density polyethylene (HDPE) finish on the top surface. It is lightweight and durable and can be mounted directly to floor studs or joists. Like Endurex 555, however, the NuPoly QuadFloor is the most expensive of the floor material options considered, challenging the budgetary constraints of the project. Since it includes a plywood layer, QuadFloor also raises similar mold concerns to the plywood-only concept. Figure 26 shows a cross-sectional view of a NuPoly QuadFloor panel.

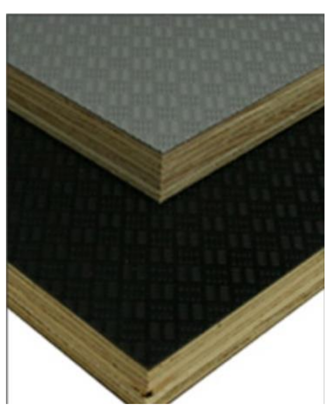


Figure 26: NuPoly QuadFloor

The third option considered was Coosa Board, a high-density polyurethane foam board reinforced with layers of fiberglass. This product is resistant to mold and typically serves as a replacement for wood when mold is of particular concern, such as in marine, industrial and transportation applications. It is just 0.75 in. (19 mm) thick and can be mounted directly to floor studs or joists and then layered with an interior finish such as vinyl. Coosa Board provides all of these features at a lower cost and weight than NuPoly QuadFloor. Figure 27 shows the Coosa Board, including a close-up view of the reinforcing fiberglass.

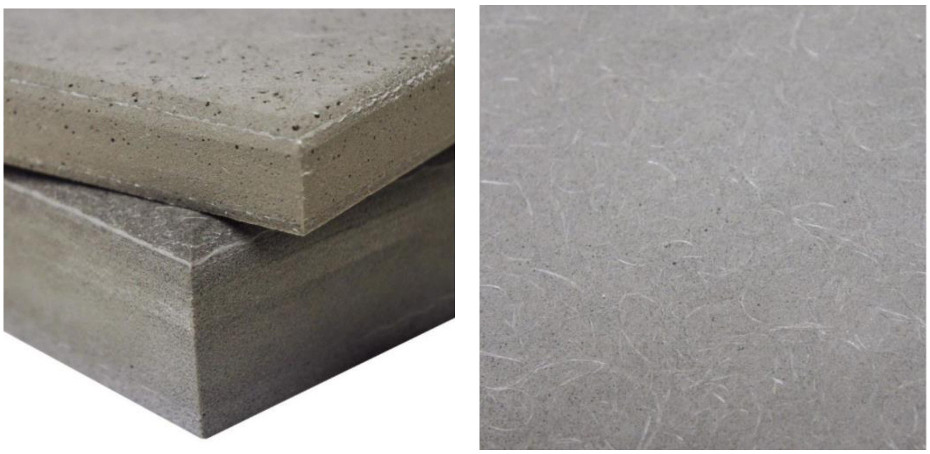


Figure 27: Coosa Board composite floor with close-up of fiberglass reinforced plastic (right)

Table 13 below summarizes values pertinent to the floor material selection.

Table 13: Floor Material Properties and Values

Product	Weight (lb/sqft)	Cost (per sqft)	Thickness (in.)	Mold-Resistant
Plywood	3.51	$1.00	0.75	No
NuPoly QuadFloor	2.65	> $10.28	1.57	No
Coosa Board	1.50	$10.28	0.75	Yes

Based on the decision matrix in Table 14, the team selected Coosa Board for use in the design. Descriptions of each parameter are provided in Table 15.

Table 14: Decision Matrix - Floor Material

Requirements	Weight (0-10)	Plywood Un-weighted (1-3)	Plywood Weighted	NuPoly QuadFloor Un-weighted (1-3)	NuPoly QuadFloor Weighted	Coosa Board Un-weighted (1-3)	Coosa Board Weighted
Withstands the environment	10	1	10	3	30	2	20
Cost	10	3	30	1	10	2	20
Easy to transport (weight/size)	8	1	8	3	24	2	16
Easy and quick set-up	8	3	24	1	8	2	16
Reusable (no mold, rust, sanitized, outgassing)	8	1	8	2	16	3	24
Climate control/insulation (AC, heating)	6	1	6	2	12	3	18
Low manufacturing time	4	3	12	1	4	2	8
FINAL SCORE		13	**98**	13	**104**	16	**122**

Table 15: Floor Material Selection Parameters

Parameter	Description
Withstands the environment	Expected lifespan of the system structure under expected loading and fatigue
Cost	Total cost of the system
Easy to transport (weight/size)	Level of difficulty required to move the system both long and short distances, based on size, shape, and weight
Easy and quick set-up	Level of difficulty required to set up the system on site, based on tools and number of people required
Reusable (no mold, rust, sanitized, outgassing)	Expected duration of use before mold, rust or outgassing issues arise
Climate control/insulation (AC, heating)	Insulation rating of the system
Low manufacturing time	Time required to purchase parts and manufacture the system

5.2.5 Wheels and Track System

The "Drawer Design" requires a track system to allow linear motion of the smaller compartments in and out of the main compartment. Four options for the wheels and track system included V-groove wheels and track, linear slides, telescoping slides, and simple rollers. Figure 28 shows the V-groove wheels and track. This ball bearing based guide wheel system has a low coefficient of friction, offering smooth and stable motion. The V-groove of the wheel coupled with the slope of the track prevents debris buildup.

Figure 28: V-groove wheels and track system

Figure 29 displays the linear slide option. The linear slide system is composed of a compact carriage assembly and a double-edged track. The track is self-aligning which speeds installation time and lowers cost.

Figure 29: Linear slide system

Figure 30 shows the telescoping option. This option is a low-profile track that slides in and out of an external track similar to that of a drawer one may find in a kitchen. This product comes as one part, and does not have an external wheel required for motion. It offers rigidity under extended loads, and smooth, quiet motion across the complete travel length.

Figure 30: Telescoping slide system

Figure 31 presents the simple rollers option. This cost-effective solution rolls on any flat surface and is versatile when mounting. These wheels would not require the purchasing of a specific track system, however they are not the most accurate form of linear motion.

Figure 31: Simple roller system

A decision matrix was used to evaluate each of the four options based on price, precision, ease of installation, weight capacity, and profile/size. Descriptions of each parameter are provided in Table 17. For each parameter, the designs were compared and given a rating of 1-4. Designs that least effectively met a specification received a 1, and designs that most effectively met a specification received a 4. The V-groove wheels and track system was selected based on the decision matrix in Table 16. This system was particularly attractive due to its weight capacity, precision, and low profile. Additional benefits include protection against debris collecting on the track due to the V shape and the ability of the wheel to roll over non-perfect transitions of track segments.

Table 16: Decision Matrix - Wheels and Track System

Parameter	Weight (0-10)	V-Groove Un-weighted (1-4)	V-Groove Weighted	Linear Slides Un-weighted (1-4)	Linear Slides Weighted	Telescoping Slides Un-weighted (1-4)	Telescoping Slides Weighted	Simple Rollers Un-Weighted (1-4)	Simple Rollers Weighted
Weight Capacity	5	4	20	3	15	1	5	2	10
Price	4	2	8	1	4	3	12	4	16
Ease of Installation	3	2	6	4	12	1	3	3	9
Precision	2	4	8	3	6	2	4	1	2
Profile/Size	1	3	3	1	1	4	4	2	2
FINAL SCORE		**15**	**45**	**12**	**38**	**11**	**28**	**12**	**39**

Table 17: Wheels and Track System Parameters and Descriptions

Parameter	Description
Weight Capacity	Weight that the system can support. The system must allow easy translation under the load of the structure.
Price	Total cost of the system
Ease of Installation	Level of difficulty required to install the system. Complicated processes increase labor costs and the likelihood of errors.
Precision	Precision required for the system to operate effectively. Greater required precision leads to higher manufacturing costs and potential system operating failure.
Profile/Size	Total size of the system. Large tracks inside the unit create a tripping hazard and reduce total living area.

The tracks will be mounted to floor studs rather than the walls because the rated capacity of the V-wheels is greater under radial loading than axial loading. To integrate the track, it is important to keep the system as low-profile as possible, providing a seamless connection between wall and floor. To achieve this, the V-track will be mounted to a strut in the floor. The wheels will then be recessed into the bottom of the PermaTherm wall panels by running a pin through the aluminum U-channels. This will allow the wall to be flush with the floor. Since the track needs to span over 20 ft (6.1 m) linearly, and the track can only be purchased in 72 in. (1.8 m) sections, it is difficult to construct a perfectly straight rail. To offset any error, only one side of the unit will use the V-wheel and track system. The other side of the unit will use a simple roller on flat bar stock. This will allow for slight transverse motion if the V-track is not perfectly parallel to the edge of the frame. Section 6.2.2 summarizes the bearing stress and tear out calculations for the wheels and track system, and Appendix B shows the full calculations.

5.2.6 Leveling System

The unit requires a leveling system to ensure that the interior floor surface is flat when the unit is expanded for use. This was achieved by mounting corrosion-resistant stainless steel leveling feet to the bottom of the unit. These feet allowed for vertical adjustment during the set-up process to account for uneven ground.

Two options were considered for this system. The first involved leveling feet mounted to all three compartments of the unit. This option caused large stresses on the feet since they were axially loaded with the entire weight of the structure. These stresses approached the critical buckling load. The second option involved leveling feet mounted only on the fold-down floors of the sliding compartments. The main compartment would be supported by a 3-in. (7.6-cm) tall base frame. The leveling feet would be adjusted accordingly to account for this difference in height along with any uneven ground. This option decreased the total load applied to the feet, but required flat ground for the main compartment. The second option was selected to ensure the leveling feet do not fail due to buckling. These buckling calculations can be found in Appendix C. Figure 32 shows a front-view comparison of the two options.

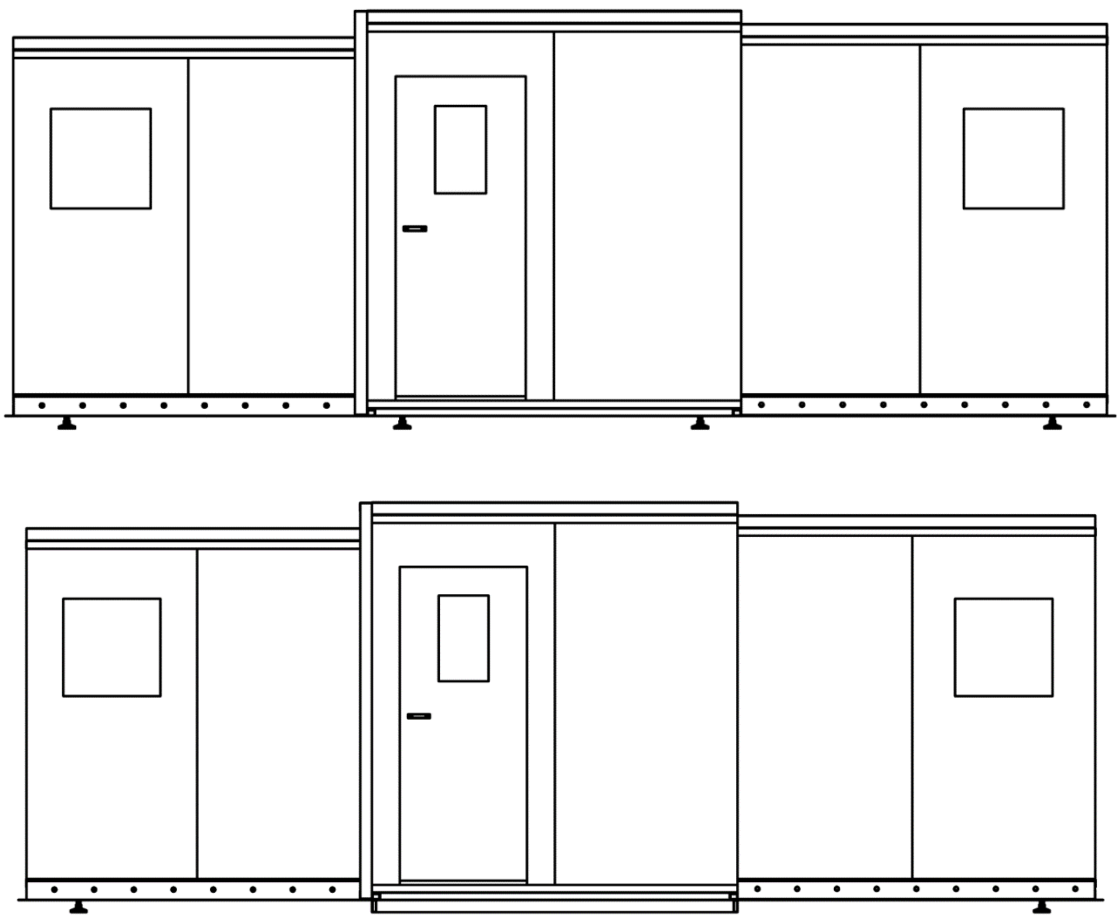


Figure 32: Leveling system option 1 (top) and option 2 (bottom)

The selected leveling feet have a 4 in. (10 cm) diameter base and a 1 in. (19 mm) diameter threaded screw that allows for a height adjustment of 8 in. (20 cm). The feet also have a ball bearing swivel with a range of motion up to 7.5 degrees (see specification sheet in Appendix D).

Figure 33 shows details of the leveling feet from the McMaster-Carr specification sheet in Appendix D.

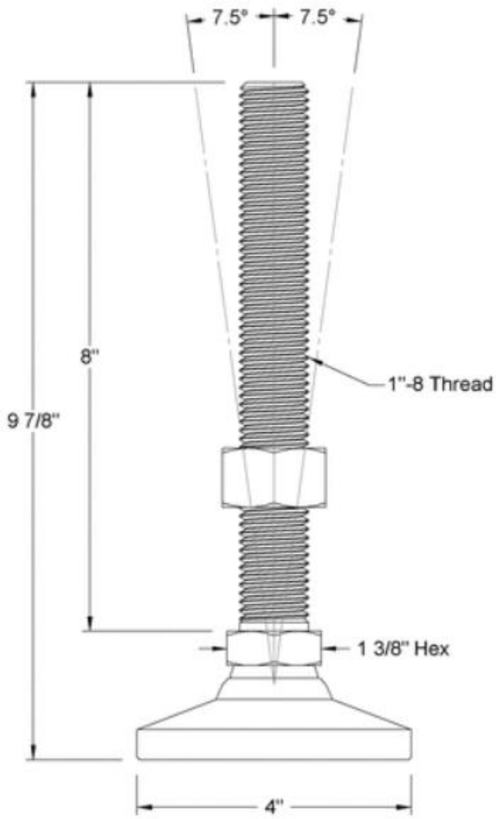


Figure 33: Corrosion-resistant stainless steel leveling feet

5.2.7 Locking Mechanism

Once each side is fully extended on the track, the compartments need to be locked in place. To achieve this, the unit will have two locking mechanisms. The first will mechanically fasten the compartment to the floor by threading six bolts through the vertical flange of an L-bracket that is connected to the unit base as seen in Figure 34. The L-bracket locking mechanism will prevent the structure from lifting off the track or sliding off the end of the track. Section 6.2.3 summarizes the calculations conducted to determine the size of this locking mechanism. Using 0.25 in. (0.6 cm) diameter steel bolts will result in a safety factor of 3.73 for axial stress at 160 mph wind speeds. Appendix E shows the full calculations.

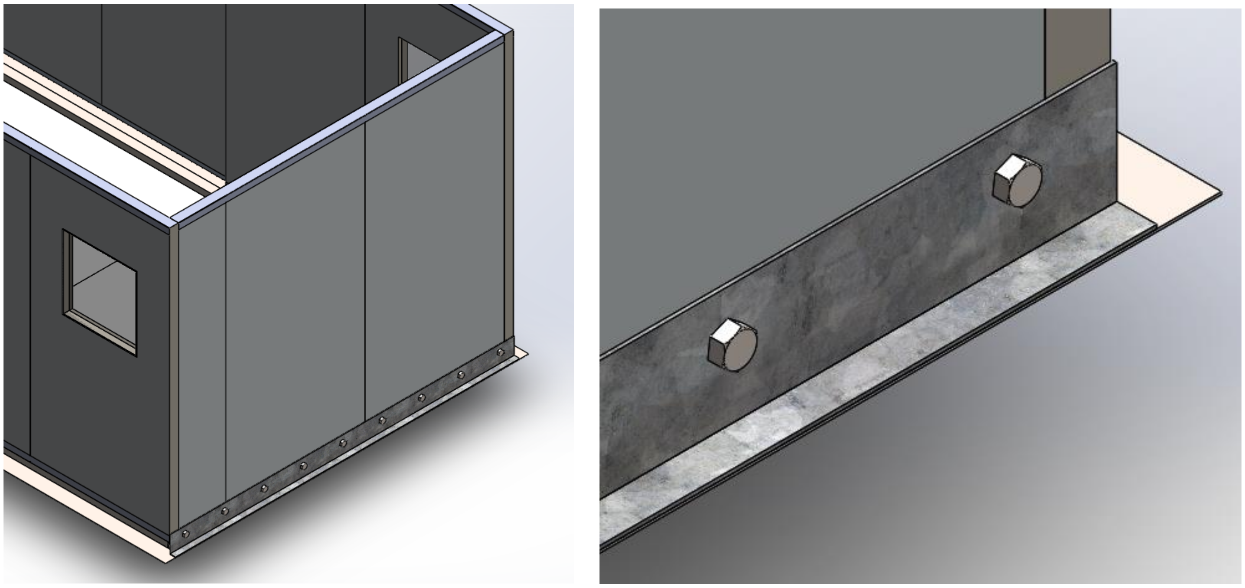


Figure 34: Locking mechanism

5.2.8 Other Systems

Electricity, air handling and plumbing systems will not be designed as a part of this project. The team will leave room in the floor to run all necessary piping based on the floor plan layout in Section 5.3. The air handling will be conducted by a window air-conditioning unit that can be installed in any window, and a vent installed in the ceiling above the shower unit. For electricity, the team will leave room along the ceiling and walls to run necessary wiring connections.

5.3 Floor Plan and Layout

The interior of the unit must include basic living requirements for up to four people. This includes plumbing (sink and shower), waste removal (toilet and shower drain), kitchen appliances (hot plate and refrigerator), and an adequate amount of floor space. The team designed the unit to contain these requirements within the collapsed unit so that they would not need to be installed separately after the unit is set up on site.

The designed kitchen area included a sink, a hot plate, counter space to prepare meals, a mini refrigerator, a microwave, and cabinet space. Based on mobile home bathrooms and typical sizes for a toilet and shower stall, a 3 x 5 ft (0.9 x 1.5 m) bathroom footprint and a 2 x 5 ft (0.6 x 1.5 m) kitchen countertop was selected as the minimum feasible footprint for these components. To centralize toilet, shower, and sink plumbing, the kitchen countertop is located along the wall of the bathroom. Figure 35 shows the proposed layout of the toilet, shower, and countertop within the collapsed unit.

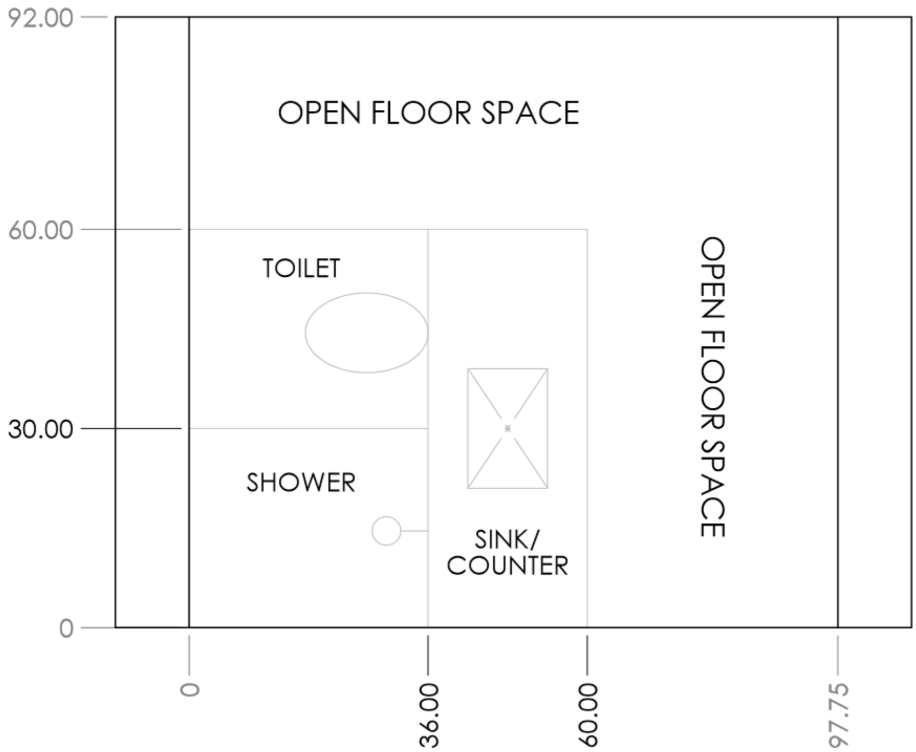


Figure 35: Proposed floor layout

The structure also required a door and windows cut into the walls. A single 32 x 80 in. (0.8 x 2.0 m) cut in a PermaTherm wall panel of the main compartment served as the entry/exit door for the unit. These dimensions comply with the 32 in. (0.8 m) minimum width for a door serving as a means of egress. Locating the door in the main compartment minimized the maximum travel distance from any point within the unit to the exit. Four 24 x 24 in. (0.6 x 0.6 m) windows were cut into wall panels on opposite sides of each sliding compartment to provide natural light and comfort throughout the interior, and to allow for mounting of an air conditioning window unit in any of the windows. Locating the windows on the sliding compartments also protected the windows from external exposure when the unit is stored in the collapsed position.

The rest of the unit is used as open living space where beds and furniture can be placed. There is extra space in the main compartment when the unit is collapsed, which allows for the storage of other items such as bed frames and foldable tables and chairs. Furniture may also be mounted to the walls of the smallest compartment and folded down once the unit is expanded. Figure 36 shows an expanded view of the front side of the unit including two windows and one door.

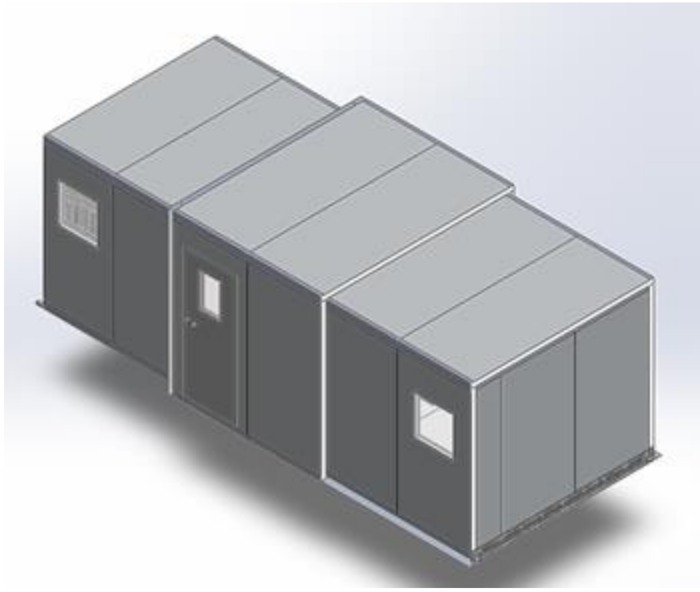


Figure 36: Expanded view of the front side of the unit showing two windows and one door

5.4 Final Design Overview

Figure 37 shows a collapsed view of the final design resulting from the design choices summarized in this chapter, including exterior dimensions that fit within the shipping constraints discussed in Section 5.2.1. These shipping constraints limit the size of the unit to 8.5 ft (2.6 m) height, 10 ft (3.0 m) length, and 8 ft (2.4 m) width. Based on product specifications and dimensions, the estimated weight of the completed unit is 4,418 lb. Table 18 shows an itemized list the weights of each unit component.

Table 18: Weight of Unit Components

Component	Material(s)	Weight (lb)
Floor Frame	Steel (various tubing)	2476
Wall and Roof Panels	26-gauge galvanized steel, EPS (PermaTherm)	1326
Subfloor	HDPE, FRP (Coosa Board)	274
U-channels	18-gauge aluminum	83
Toilet	Vitreous china	77
Fridge	Stainless steel	52
Counter/Sink	Wood, stainless steel	50
Wheels and Track	Stainless steel	39
Shower	Composite	36
Fasteners	Steel	5
	Total:	**4418**

These dimensions and weight will allow five units to be transported on one trailer. Figure 37 also shows an expanded view of the final design with exterior dimensions included. The interior includes about 200 ft^2 (18.6 m^2) of floor space, enough for up to five occupants based on the requirement of 40 ft^2 (3.7 m^2) per person residing in the unit (see Section 3.2.5). This exceeds the design goal of four occupants.

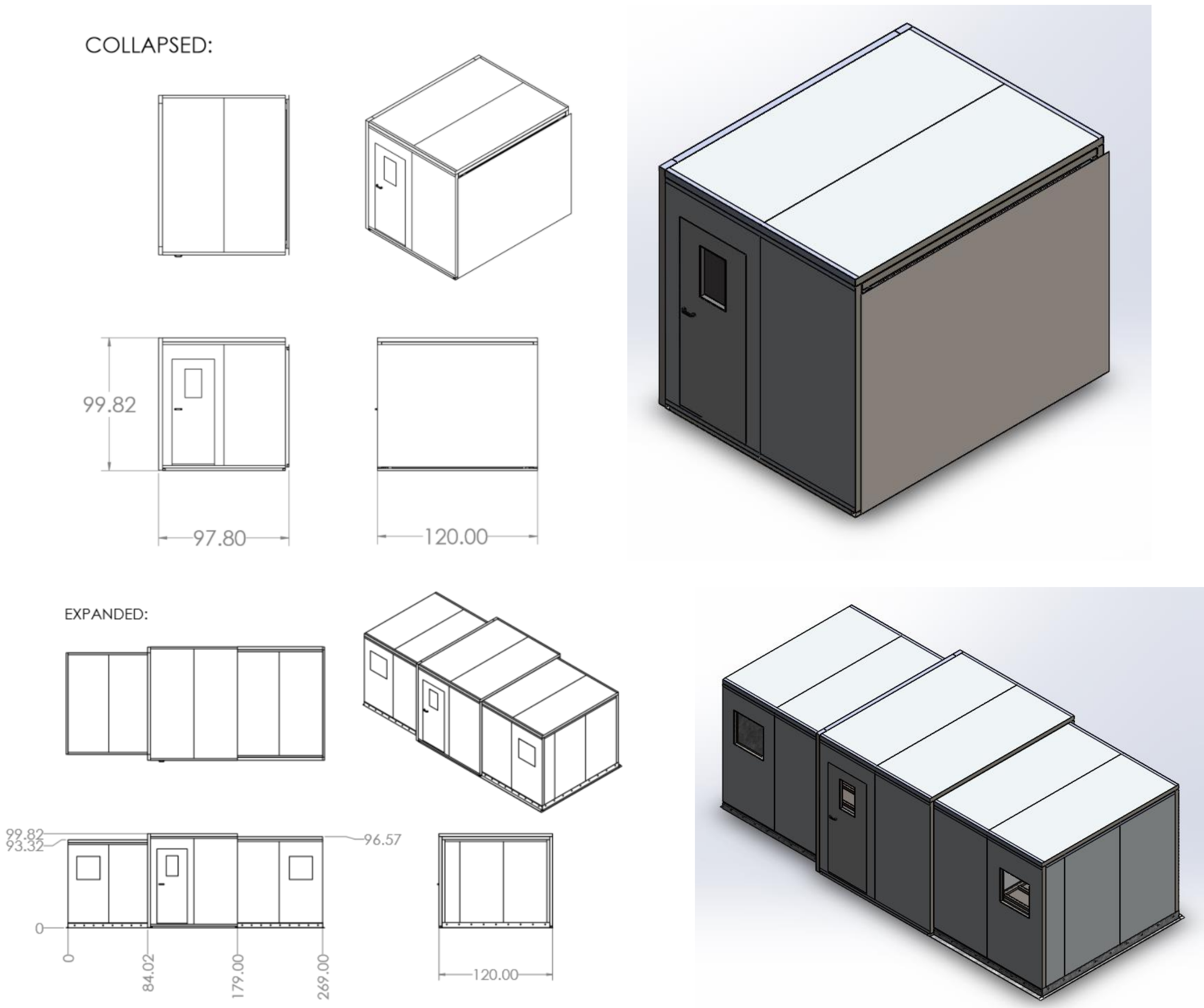


Figure 37: Final design, collapsed (top) and expanded (bottom) views (units: in.)

Figure 38 shows a cross-sectional model of the interior of the unit in both the collapsed (left) and expanded (right) positions. The views include a toilet, a shower unit, and one set of bunk beds, but do not include any other amenities. Also shown is one entry door on the main compartment of the structure that is 32 in. (0.8 m) wide by 80 in. (2.0 m) tall. Lastly, four 24-in. x 24-in. (0.6 m x 0.6 m) windows are included, one on each side of both sliding compartments.

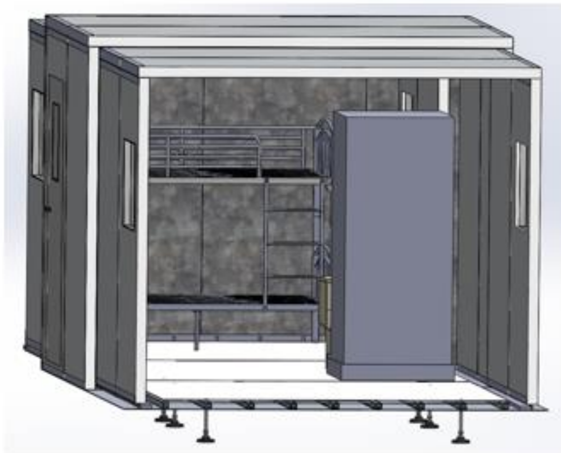
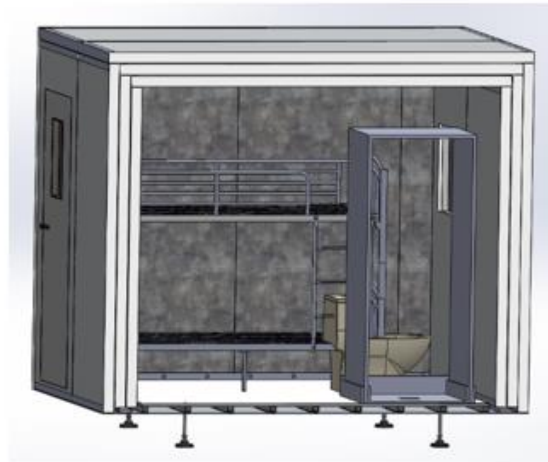



Figure 38: Final design cross-sectional view, expanded (left) and collapsed (right)

The bill of materials in Table 19 provides a complete list of materials required to build the unit, along with the quantity and cost of each item. The resulting total material cost for construction of a single unit is $15,435.32. This figure is slightly above the $15,000 target manufacturing cost per unit. It does not account for labor costs, nor does it account for potential savings due to mass production.

Table 19: Bill of Materials

Item	Manufacturer	Part Number	Description	Application	UOM	Qty	Cost	Total Cost
Leveling Feet	McMaster-Carr	6111K96	Corrosion-Resistant Swivel Leveling Mounts with Threaded Stud	Leveling	Each	8	77.40	$619.20
Hinges	McMaster-Carr	16175A37	Metal Surface-Mount Hinges	Collapsing	Each	10	8.02	$80.20
Toilet	Home Depot	Model # N2428RB/N2428T	2-piece 1.28 GPF High Efficiency Single Flush Round Toilet in White	Amenitites	Each	1	88.00	$88.00
Shower	Home Depot	Model # 68	32 in. x 32 in. x 75 in. Shower Stall with Standard Base in White	Amenitites	Each	1	193.00	$193.00
Sink	Home Depot	Model # HD320874LFR	All-in-One Drop-in Stainless Steel 15 in. 2-Hole Single Bowl Bar Sink	Amenitites	Each	1	99.00	$99.00
Fridge	Home Depot	Model # WHD113FSS1	3.1 cu. ft. Double Door Mini Refrigerator/Freezer in Stainless Steel	Amenitites	Each	1	179.72	$179.72
Floor Panels	Boat Outfitters	SKU# 13770-42332-cp	Coosa composite board - bluewater 26	Floor	Each	8	328.90	$2,631.20
Rolling Wheels, V-Track	BishopWisecarver	W4X	Wheel Steel Sealed/shield	Collapsing	Each	6	42.86	$257.16
Rolling Bushings	BishopWisecarver	B4SS	Bushing SS CON	Collapsing	Each	6	4.91	$29.46
Rolling Tracks	BishopWisecarver	T4730019	TRACK CARBON STEEL	Collapsing	Each	6	157.85	$947.10
Rolling Wheels	BishopWisecarver	LJ545ENS	JOURNAL ASMB - NITRILE SEALED	Collapsing	Each	6	98.72	$592.32
Shipping	Permatherm		LTL Shipment of material	Structure	Each	1	2,645.00	$2,645.00
Walls/roof	Permatherm		3" wall and roof panel	Structure	Each	1	5,882.96	$5,882.96
Floor Studs	Pacemaker		1 3/4, 24' 11 ga square tube	Floor	Each	9	45.00	$405.00
Track Studs	Pacemaker		3x 1-1/2 24' 11 ga rec tubing	Floor	Each	3	61.00	$183.00
Cross Studs	Pacemaker		2 x 1-1/2 24' 11 ga rec tubing	Floor	Each	3	48.00	$144.00
Fixed Floor	Pacemaker		3 x 1 24' 11 ga rec tubing	Floor	Each	7	53.00	$371.00
Fork Pockets	Pacemaker		4'x8' HR sheet	Floor	Each	1	88.00	$88.00
								$15,435.32

Chapter 6: Analysis and Verification

6.1 Finite Element Analysis (FEA)

The finite element analysis (FEA) software ANSYS was used for evaluation to confirm the structural integrity of the design based on stress and deformation. ANSYS outputs stress and deformation values for a series of points throughout the physical model being analyzed. These points are referred to as nodes. The appropriateness of FEA methods was first verified through hand calculations and proper mesh sizing was confirmed through a convergence study. Results were then obtained and compared to failure criteria to develop safety factors.

6.1.1 Validation through Hand Calculations

To verify the appropriateness of the model, a distributed load beam bending problem was modeled in ANSYS. The results were compared to hand calculations completed using Mathcad software.

The calculation was performed by modeling a 4 x 8 ft (1.2 x 2.4 m) PermaTherm wall panel as a vertical cantilever beam fixed at the bottom. A pressure of 58.3 PSF (2.79 kPA) was applied to the face of the wall to model the 146 mph (65.3 m/s) winds of a Category 5 hurricane. Wind speed is converted to pressure using the Ensewiler equation (National Certified Testing Laboratories, 2018):

$$P = 0.00256 * v^2$$

Where P is the pressure due to wind (PSF) and v is the wind speed (mph). To calculate maximum deflection, the team used the deflection equation of a cantilevered beam:

$$\delta = \frac{wh^4}{8EI}$$

Where δ is the deflection (ft), w is the pressure due to wind (lb/ft), h is the height of the panel (ft), E is the elastic modulus of the material (PSF), and I is the moment of inertia (ft^4).

For normal stresses the team used the formula for bending stress and axial stress to calculate the stresses along the height of the panel:

$$\sigma_b = M * \frac{c}{I}$$

$$\sigma_a = \frac{F_w}{A}$$

Where σ_b is normal stress due to bending (MPa), M is the moment around the base of the panel (N*m), c is the distance from the neutral axis (m), I is the moment of inertia (m^4), σ_a is axial stress (MPa), F_w is the force due to the panel weight (N), and A is the cross-sectional area of the panel (m^2). These calculations assume that the stresses in the panel are evenly distributed along the 4 ft (1.219 m) depth of the panel. The hand calculations are a 2D model rather than the 3D model developed in ANSYS. To account for this discrepancy, the team took the average of several values evenly distributed along the bottom edge of the ANSYS model where the stress would be the highest. The full calculations can be found in Appendix F.

The comparison of the normal stress and maximum deflection values in Table 20 shows the comparison of ANSYS and Mathcad results. Based on percent error of results, the team concluded that the values were similar enough to validate the accuracy of ANSYS modeling.

Table 20: Comparison of ANSYS and Mathcad Results

Value	ANSYS	MathCAD	% Error
Maximum Compressive Stress (MPa)	77.835	77.365	0.61
Maximum Deflection (mm)	42.941	45.165	5.18

6.1.2 Mesh Convergence Analysis

A mesh convergence analysis was performed for each FEA application to optimize the accuracy of results achieved in relation to computation time. Multiple instances of the same analysis were performed on a simplified wall panel while decreasing the mesh size. The wall panel was modeled in ANSYS, fixed at all four ends of the panel with a 58.3 PSF pressure applied normal to the front face. Figure 39 shows the setup of the wall panel.

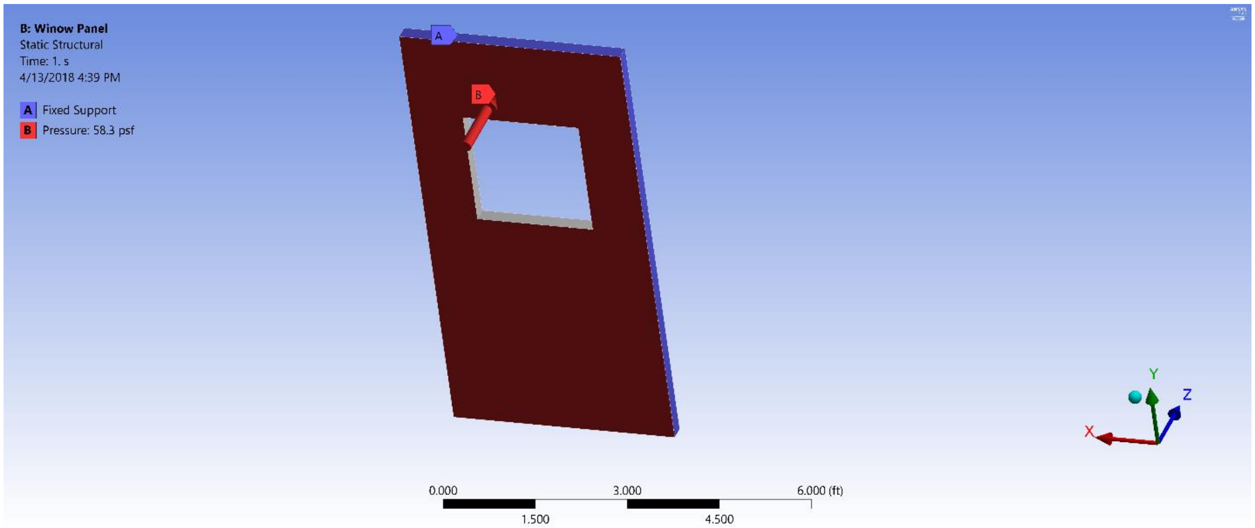


Figure 39: ANSYS wall panel set up for mesh convergence analysis

Throughout this analysis, the deformation and stress in the panel was investigated in the same locations as the mesh decreased. Using a probe, one deformation value at the middle of the panel was evaluated, along with three stress values. These locations can be seen in Figure 40, where the panel had a mesh size of 100 mm.

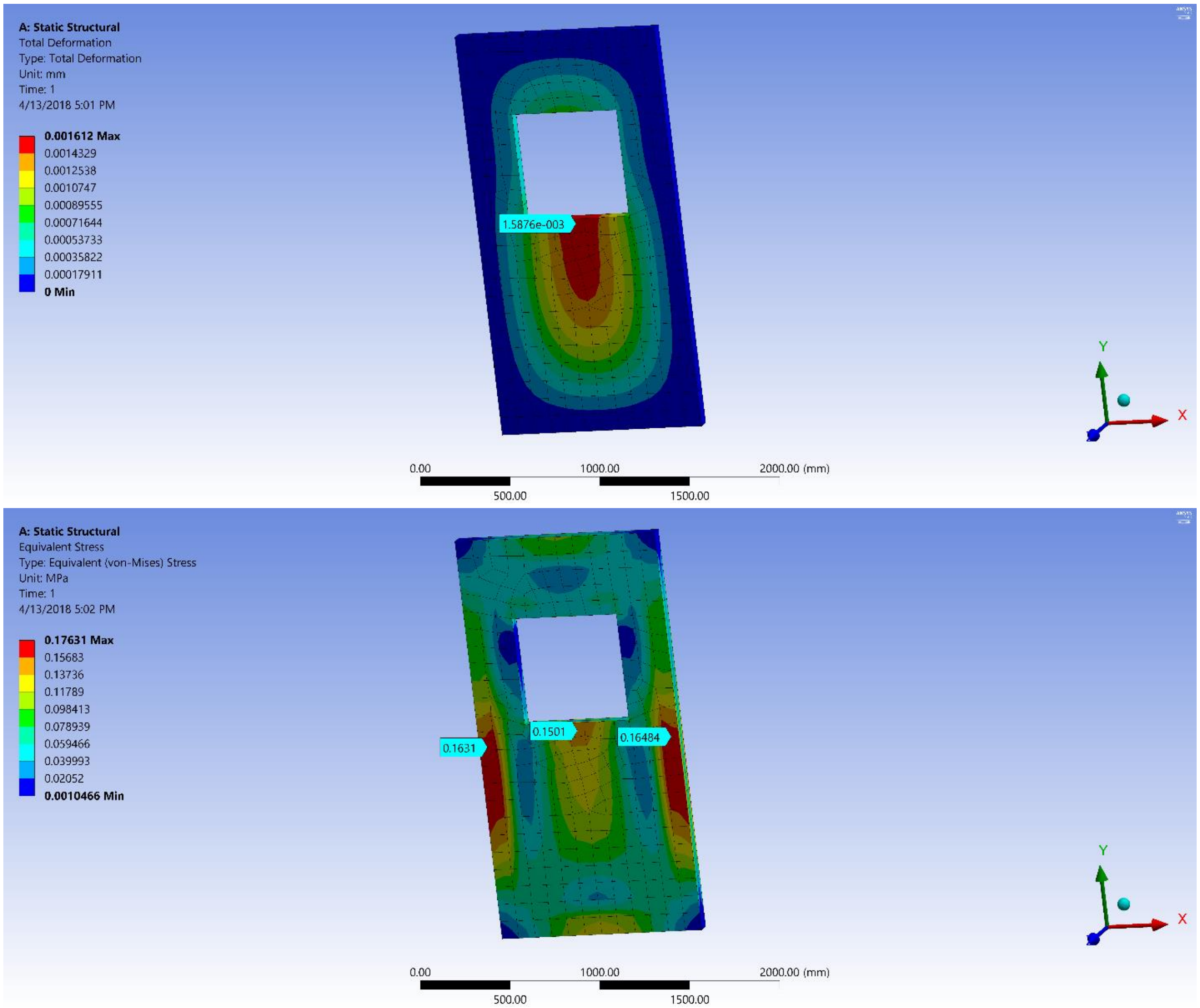


Figure 40: Measured stress and deformation values, 100 mm mesh

These four values were inspected as the mesh ranged from 100 mm to 10 mm. The results of the convergence analysis can be seen in Table 21 and Figure 41.

Table 21: Mesh convergence analysis results

Mesh Size (mm)	Deformation Middle (mm)	Stress Middle (MPa)	Stress Left (MPa)	Stress Right (MPa)
100	0.0015876	0.1501	0.1631	0.16484
75	0.001637	0.15313	0.18442	0.18175
50	0.0016431	0.15507	0.18484	0.18234
25	0.001643	0.15513	0.18491	0.1825
15	0.0016438	0.15527	0.18485	0.18228
10	0.0016439	0.15531	0.18483	0.18224

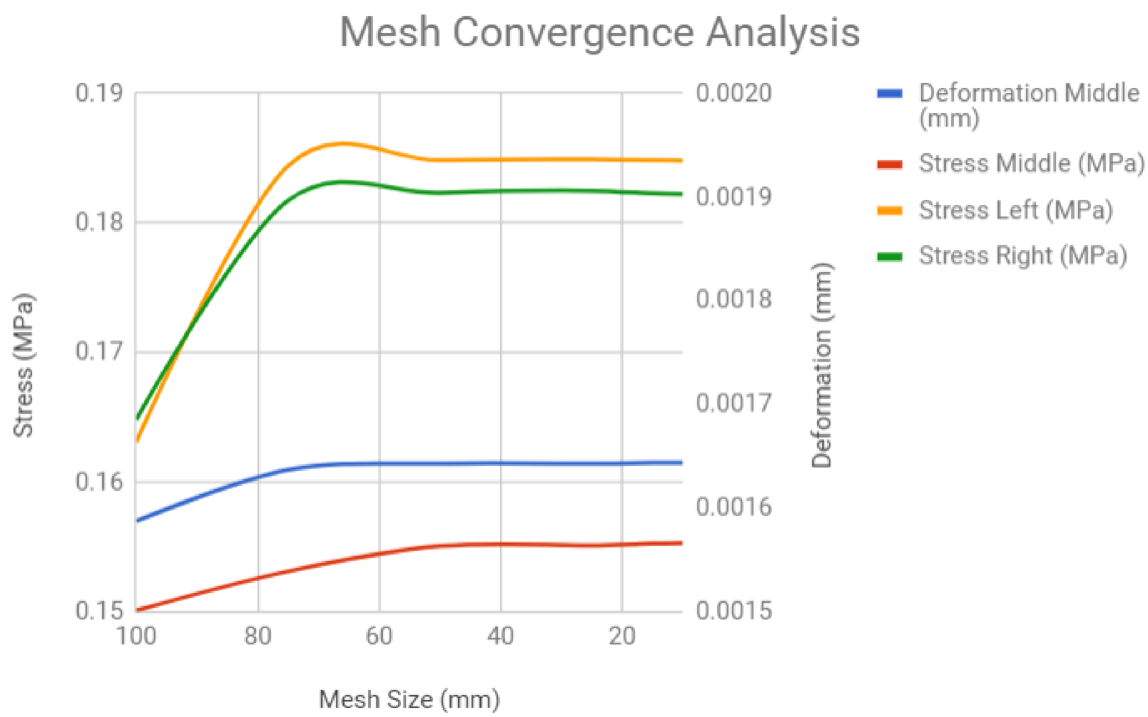


Figure 41: Mesh convergence analysis results

Based on the mesh convergence analysis, a mesh size of 50 mm (2.0 in.) was selected for the open structure because the mesh converges at a larger mesh size.

6.1.3 Finite Element Analysis (FEA) Results

6.1.3.1 Walls and Roof

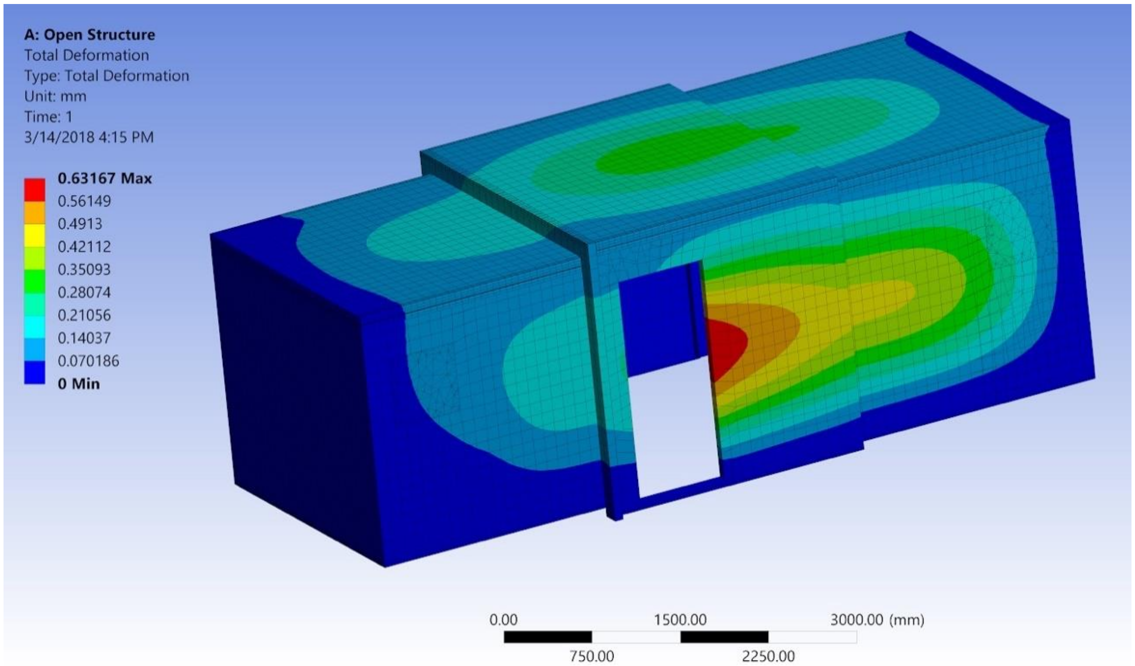
The PermaTherm wall and roof panels were configured and modeled in ANSYS to verify that the panels can withstand the Miami-Dade County hurricane wind load requirement of 146 mph, per standard ASCE 7-98. PermaTherm recommends limiting deformation of the panels to L/240, meaning for an 8-ft (2.4-m) panel, deformation should not exceed 0.4 in. (10 mm) when fixed on the top and bottom surfaces. Additionally, the yield strength of the steel on the outside of the PermaTherm panel is 250 MPa.

This section summarizes the analysis strategy for assessing the walls and roof of the unit. First, the worst-case wind orientation was determined by applying a constant wind load to the structure at multiple angles and determining the angle at which the wind resulted in the largest deformation and stress in the structure. Then, wind loads of varying intensity were applied to the structure in the worst-case orientation to develop a relationship between wind speed and the maximum deformation and stresses in the structure.

A simplified structure with no floors was modeled in ANSYS. The U-channels at the bottom of the wall panels were fixed to simulate the floor being attached to the ground, and a downward gravitational force was added to the model. To thoroughly analyze the deformation and stress in the structure and find the worst-case scenario due to wind loads, the wind pressure was applied in three orientations. A 58.3 PSF pressure (146 mph) was applied normal to the front face of the open structure, which has the largest surface area. The pressure was also applied normal to the side face of the structure, and at 45° from the faces of the structure. The results of the three scenarios can be seen in Figure 42, Figure 43, and Figure 44. The maximum deformation and stress occurred when the pressure was applied to the front face of the structure. This orientation involved the largest surface area exposed to wind, which maximized the total wind force. Table 23 shows the maximum deformation and stress values measured for each wind orientation.

Table 22: Maximum Deformation and Stress for various wind orientations (146 mph wind)

Wind Applied to:	Maximum Deformation (mm)	Maximum Stress (MPa)
Large Face	0.632	27.3
45° from Face	0.487	25.3
Small Face	0.353	11.5



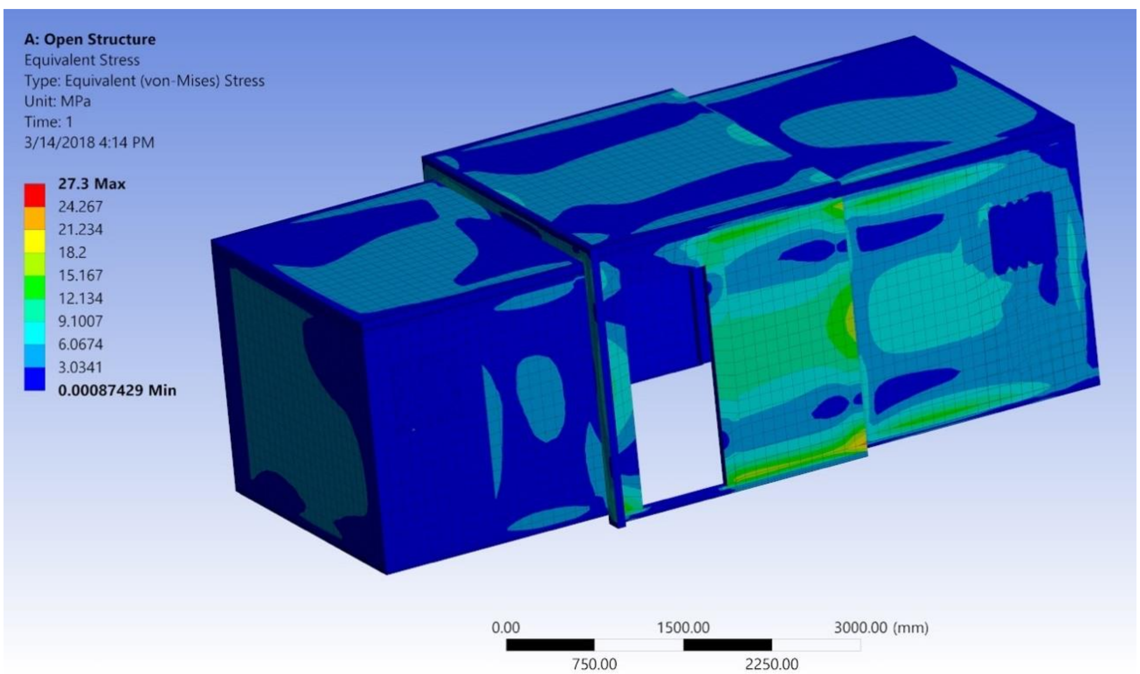
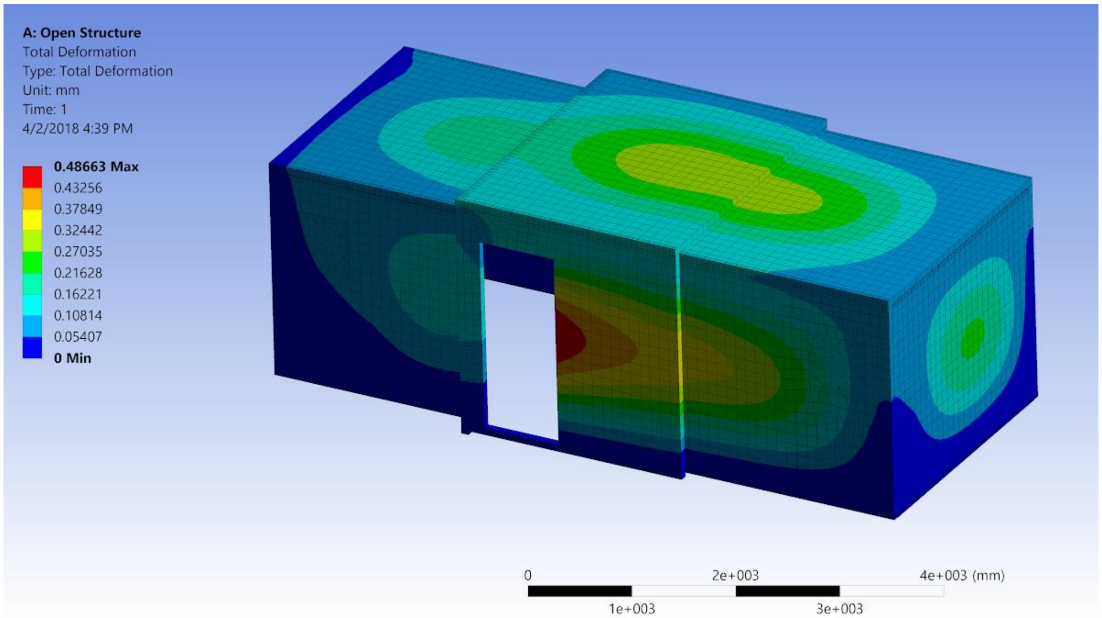


Figure 42: Deformation and Stress, 146 mph wind (large face)



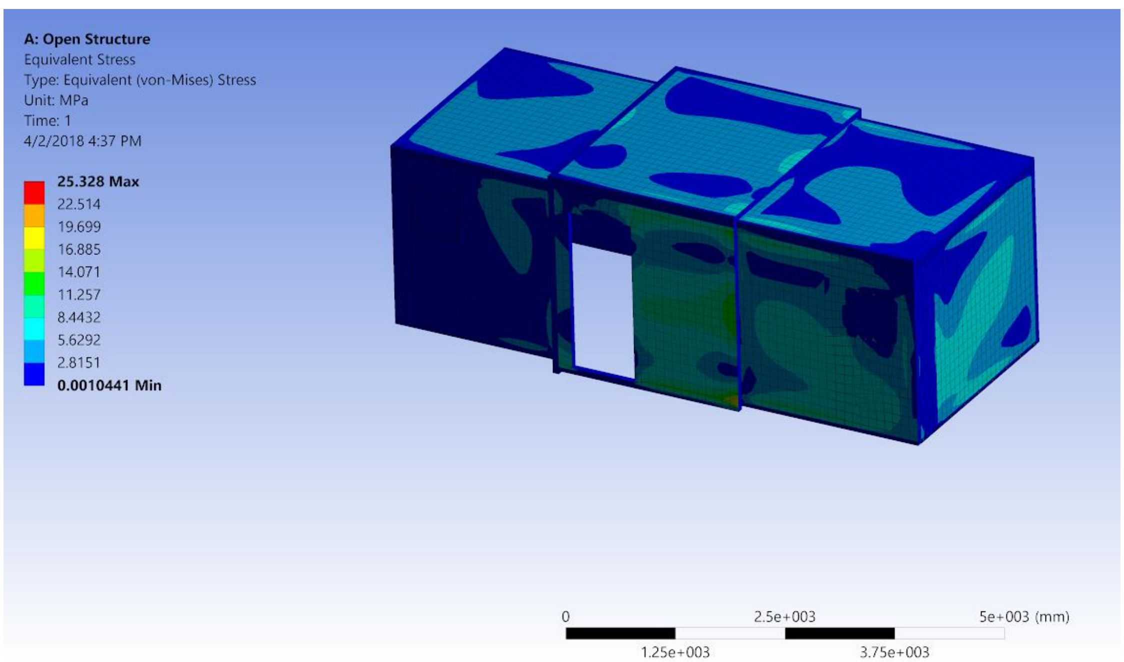


Figure 43: Deformation and Stress, 146 mph wind (45 degrees from face)

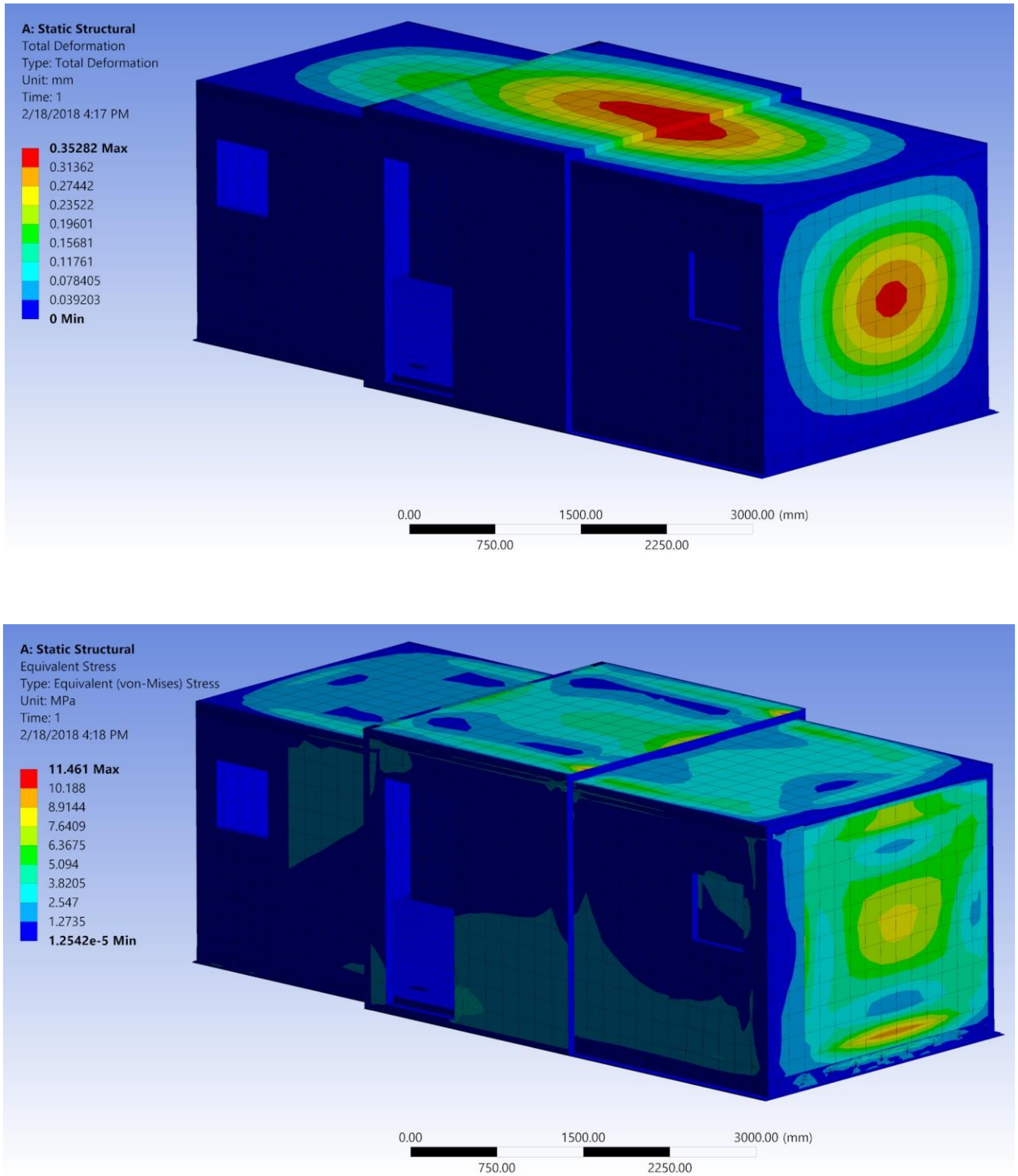


Figure 44: Deformation and Stress, 146 mph wind (small face)

To simulate and analyze the worst-case wind orientation further, the calculated pressure values for winds ranging from 9 mph to 253 mph were applied to the face of the structure with the largest surface area. The range started at 9 mph (4.0 m/s) to model the average wind speed seen in the Miami-Dade County. The maximum tested wind speed of 253 mph (113.1 m/s) was derived from the highest wind speed ever recorded, occurring during a storm on 10 April 1996

(Weather Channel). Figure 45 depicts the model utilized for analysis. The maximum Von-Mises stresses and deformations were evaluated to check for failure.

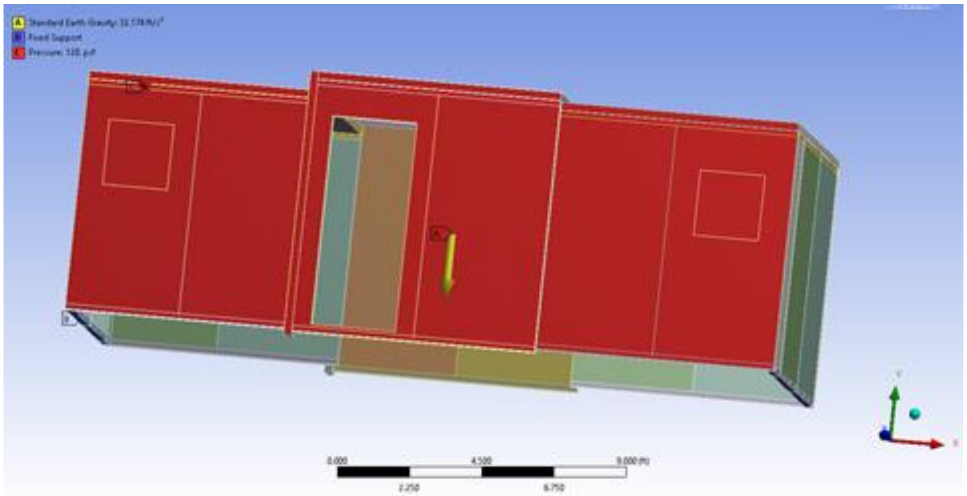


Figure 45: Model set-up for wind load analysis

For wind speeds from 0-100 mph, the maximum deformation and stress concentration was located on the roof (due to gravity) as seen in Figure 46 for 9 mph wind. The deformation and stress values decreased slightly as wind speeds increased to 100 mph because the pressure from the wind partly counteracted the downward force of gravity on the roof.

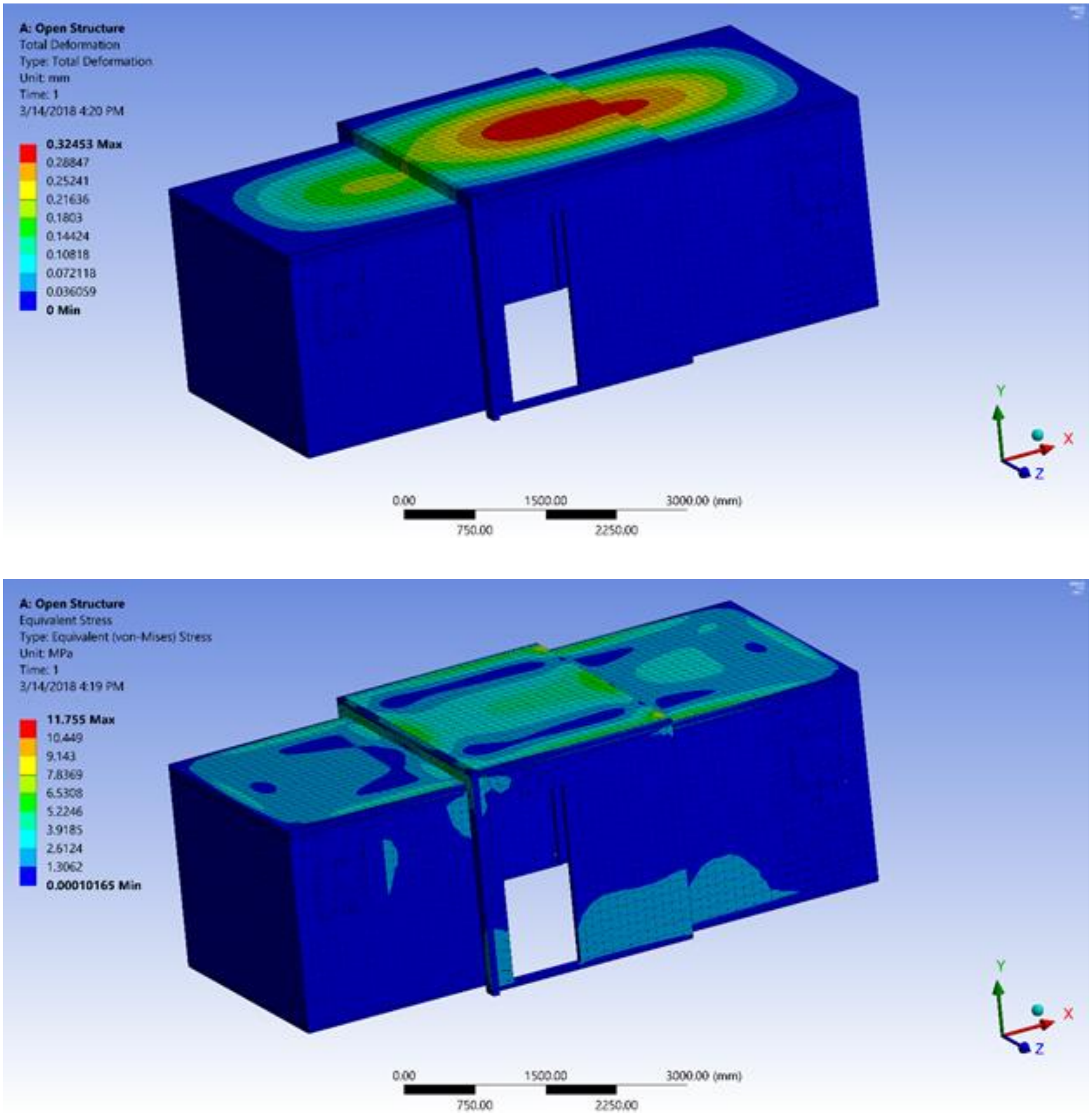


Figure 46: Deformation and Stress (9 mph wind)

Once the wind speed reached 110 mph, the magnitude of stress and deformation caused by the wind force parallel to the roof exceeded that caused by gravity in the downward direction. The maximum deformation and stress concentration locations shifted to the front face of the structure, where the pressure was applied. Figure 47 shows the deformation and stress of the structure at 110 mph. The largest deformation value is seen at the door and the largest stress value occurs at the lower right corner of the main compartment.

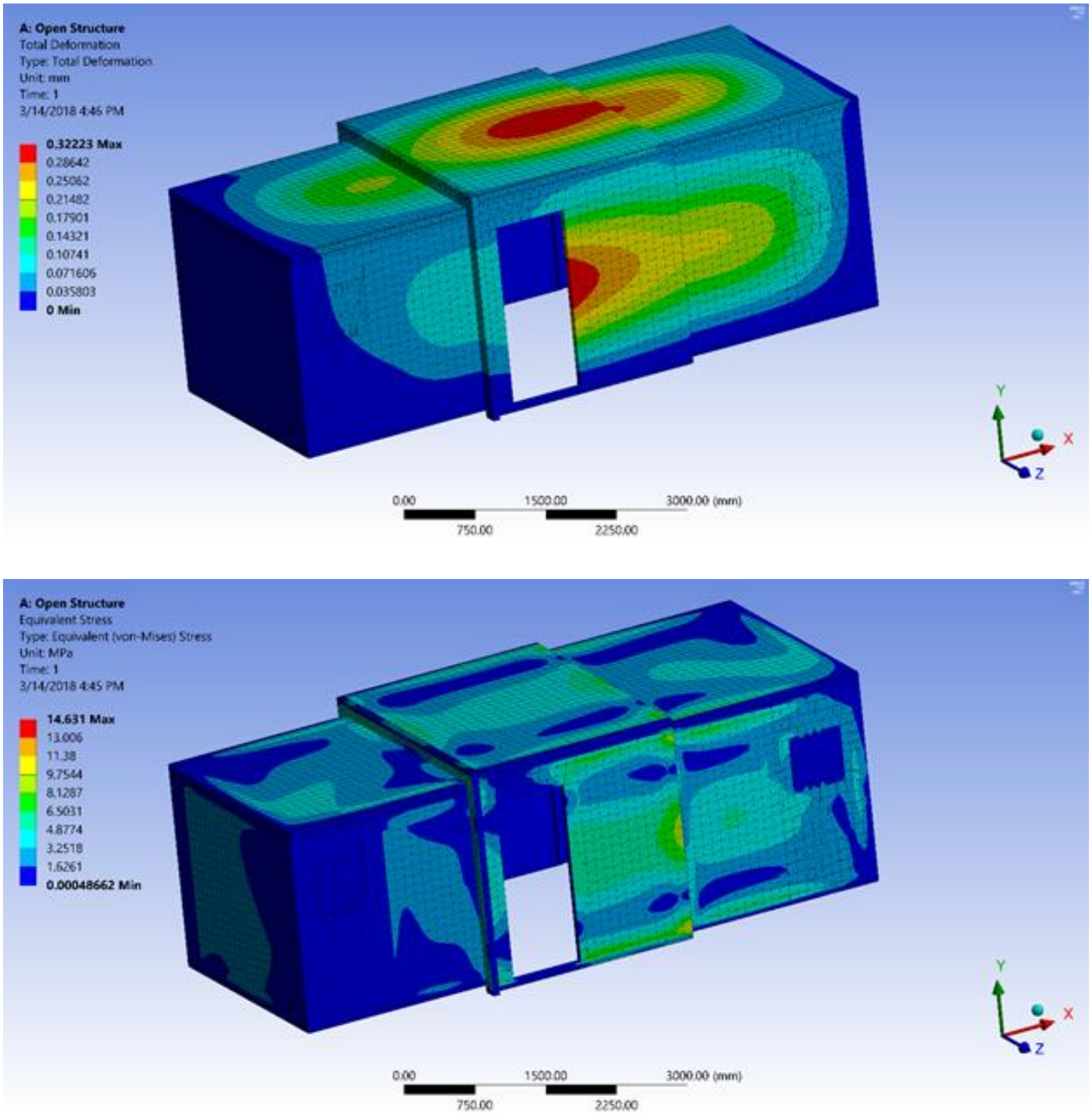


Figure 47: Deformation and Stress (110 mph wind)

Figure 48 depicts the maximum deformation and stress at 146 mph. The maximum deformation occurs at the right side of the door (shown in red in Figure 48), due to the longer length of the wall from the corner. The maximum stress is seen at the lower right corner of the main compartment. This occurs due to the fact that there is no wall support where the middle and main compartment connect. Between the small and main compartment, there is an arch of PermaTherm to reduce the gap between the two, which supports the main compartment by creating a corner. This support does not exist on the other side, therefore creating a larger stress concentration along that side of the wall. Throughout the simulations, the failure criteria of 250 MPa yield strength and 10 mm maximum deformation were not exceeded. Based on the result trends, the maximum stress on the structure would reach the failure point of 250 MPa before the deformation exceeded 10mm. Therefore, the safety factor of the structure was calculated based on the maximum strength criteria. At a 146 mph (65.3 m/s) wind speed, the structure has a stress failure safety factor of 9.1.

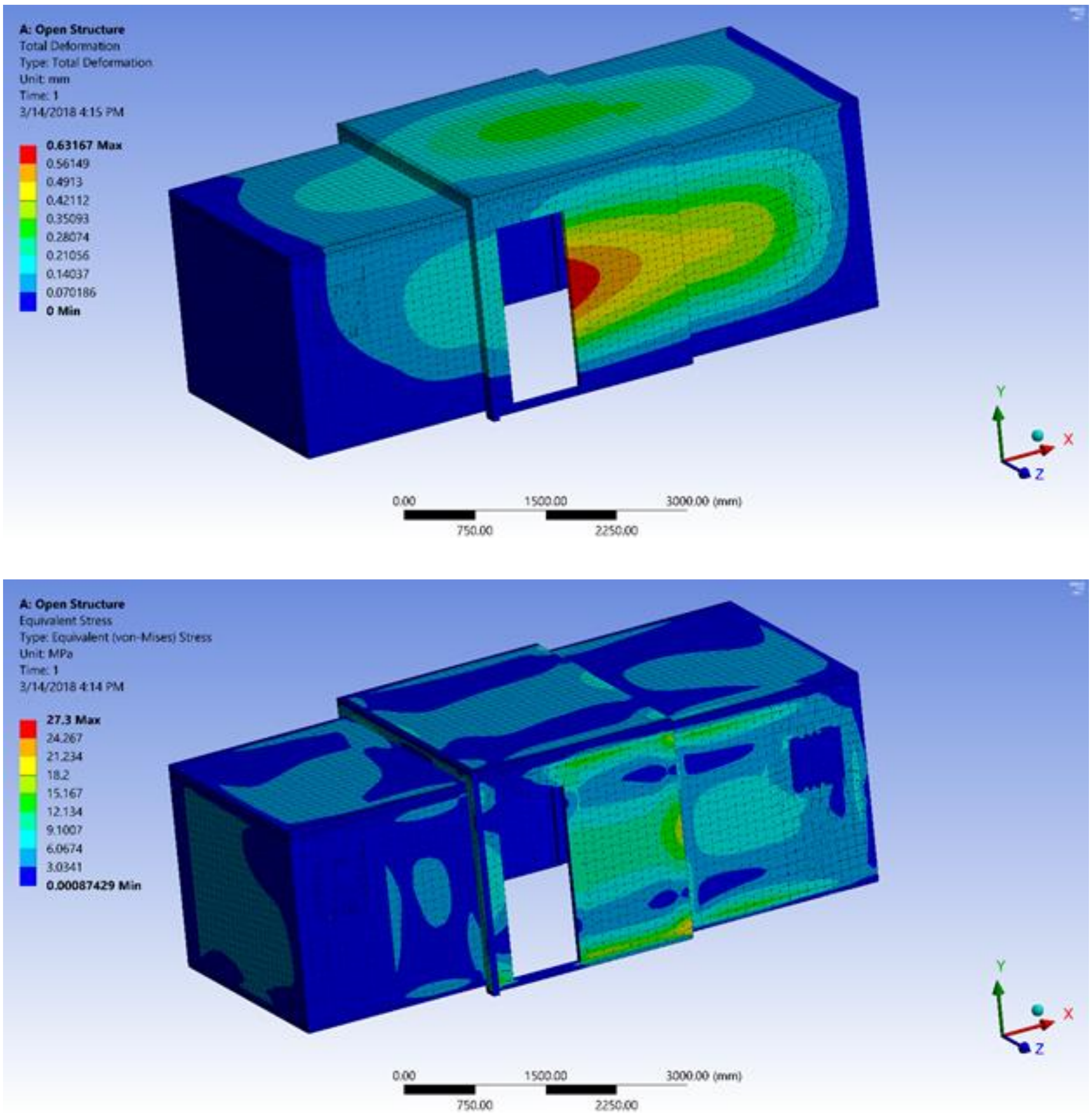


Figure 48: Deformation and Stress (146 mph wind)

Table 23 shows the data obtained from the simulation for the range of analyzed wind speeds. Figure 49 graphically represents the data and illustrates two distinct ranges of values. From 0-100 mph winds, the maximum stress and deformation values are dominated by gravitational effects and as such remain constant. For winds greater than 100 mph, the wind load has a greater effect than gravity on the stress and deformation values, and the values continue to increase as the wind speed increases.

Table 23: Maximum Von-Mises stress and deformation for various wind loads

Model:		Open Structure (big face)	
Wind Speed (mph)	Pressure (psf)	Maximum Deformation (mm)	Maximum Stress (MPa)
9	0.203	0.3245	11.755
45	5.07	0.3219	11.724
80	16.05	0.31697	11.654
110	30.34	0.3222	14.631
146	58.3	0.6317	27.3
210	109.81	1.3146	55.257
253	159.38	1.7362	72.854

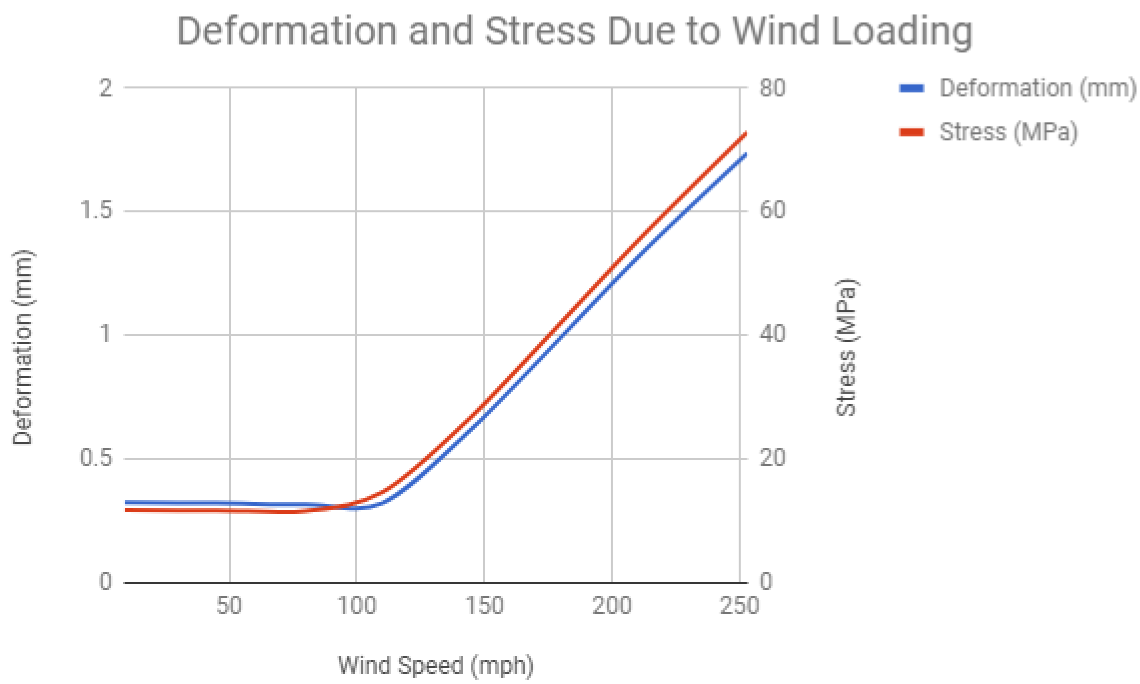


Figure 49: Maximum Von-Mises stress and deformation for various wind loads

6.1.3.2 Floor

To analyze the Coosa Board for structural stability, the team performed FEA on a floor panel consisting of 1.75-in. (44-mm) steel square tube studs with 12-in. (30-cm) spacing, layered with Coosa Board and a thin vinyl finish. The leveling feet were fixed to the ground. Figure 50 shows deformation results for modeling of a 10,000 lb (44,000 N) evenly distributed load across the area of the floor, intended to represent a conservative value for unit contents. Figure 51 shows deformation results for modeling of a 200 lb (890 N) point load centered between studs, intended to represent a typical male walking on the floor (Body Measurements, 2017). Modeling the weight of a person as a point load is a conservative representation of the actual weight distribution.

The Coosa Board has a limiting deformation of L/d = 16, which allows for 1.1875 mm deformation for a 0.75 in. (19 mm) thick panel (see specification sheet in Appendix D). The calculated deformation of the board is 0.735 mm with the analyzed distributed load and 0.04 mm with the point load. Therefore, the deformation safety factor for the floor under these loading conditions is 1.6.

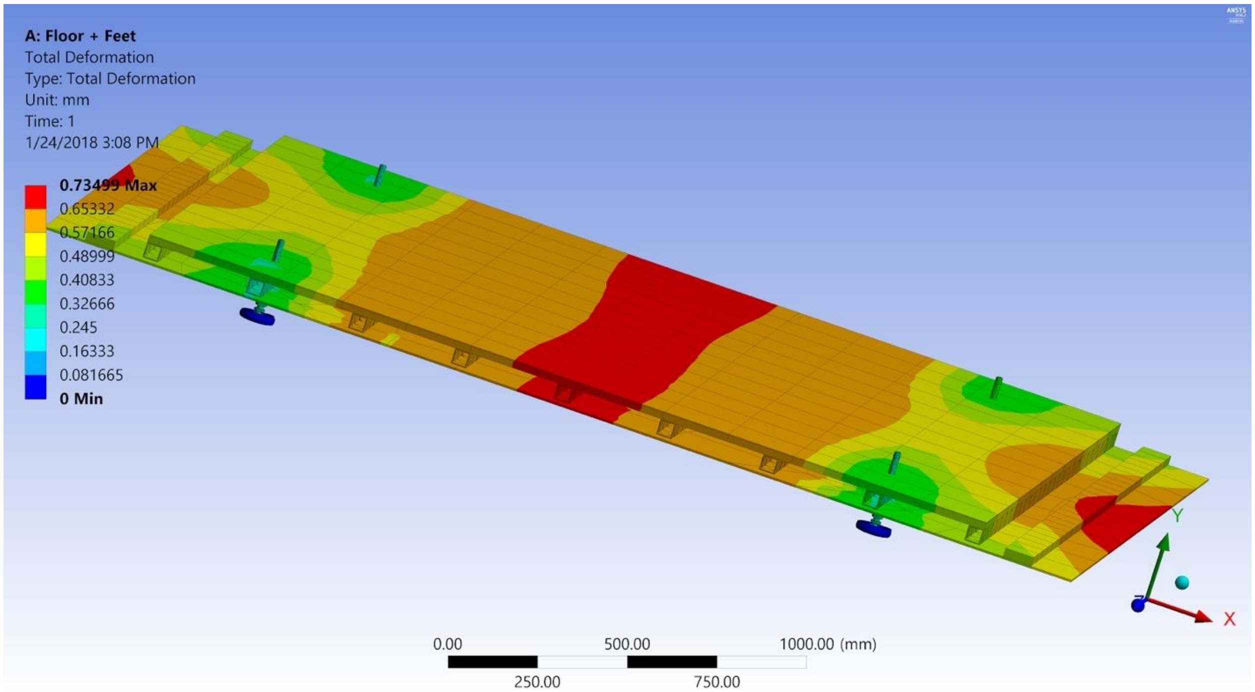


Figure 50: Floor Assembly Deformation (10,000 lb distributed load)

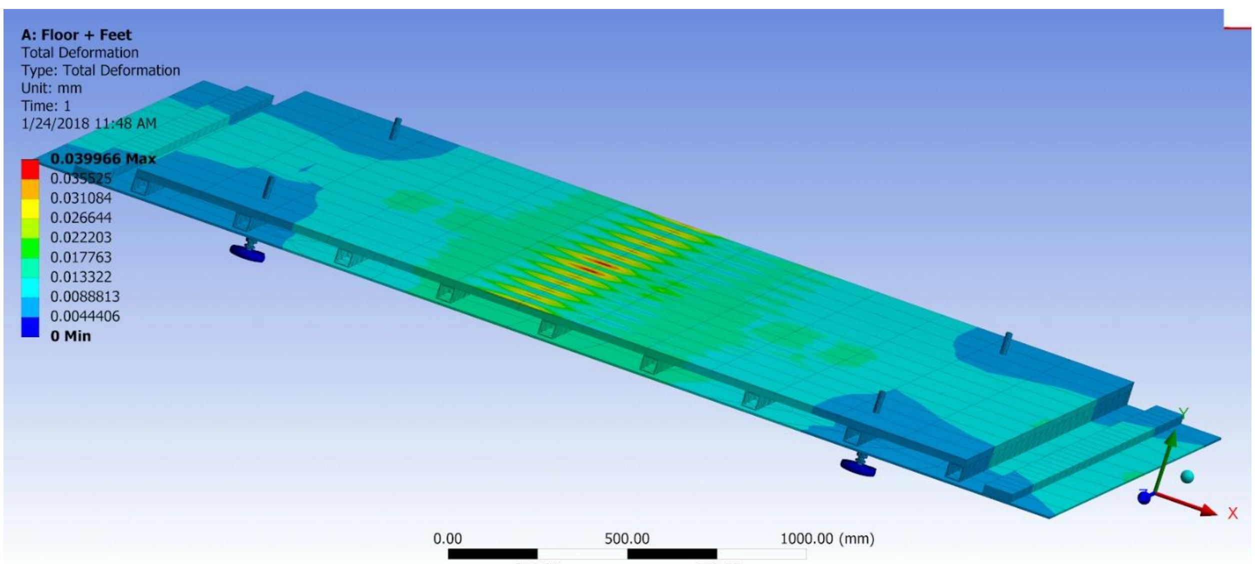


Figure 51: Floor Assembly Deformation (200 lb point load)

6.2 Component Stress Analysis

For each pin and joint required for the design, stresses were calculated to determine optimal materials and dimensions. A safety factor of at least 3 is recommended for analytical models for loading and stress that approximately represent the system (Norton, 2014). From the solutions with a safety factor of at least 3, an option was selected based on cost. These calculations were completed using Mathcad software.

6.2.1 Hinges

The hinges which attach the folding floors to the main floor must withstand the forces due to the weight of the folding floors whenever the unit is collapsed. This was modeled as double shear (as shown in Figure 52) since there would be no bending in the hinge. The weight seen on each hinge was determined by equally dividing the weight of the entire wall by the number of hinges used. Bearing stresses were calculated and the maximum was used to find the safety factor associated with the hinge using the equation:

$$\sigma_{\text{floorbear}} = \frac{F_h/2}{t_{floor} D_p}, \sigma_{\text{basebear}} = \frac{F_h}{t_{base} D_p}$$

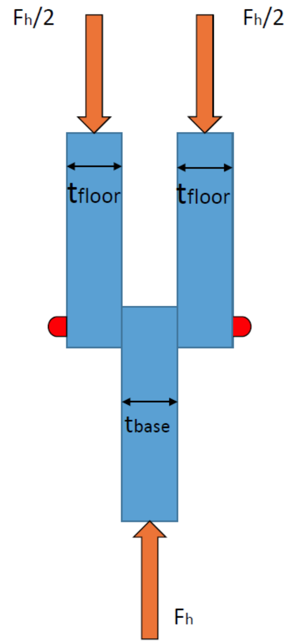


Figure 52: FBD of Hinge Pin Calculations

Where $\sigma_{\text{floorbear}}$ is the bearing stress (psi), σ_{basebear} is the bearing stress (psi), F_h is the weight of the floor acting on the hinge (lbf), t_{floor} is the width of the hinge flange (in.), t_{base} is the width of the hinge flange (in.), and D_p is the pin diameter (in.). The shear stress was also calculated using the equation:

$$\tau = \frac{F_{hf}}{2 * \frac{\pi}{4} * {D_p}^2}$$

After changing inputs such as number of hinges, diameter of the pin, and material of the hinge, 2 steel hinges with a pin diameter of 3/8 in. was selected for the design. This had a safety factor of 25.6. The full calculations can be found in Appendix G.

6.2.2 Pins – Wheels

It is important that the wheels and axle can withstand the weight of an entire compartment to allow the user to move the structure with ease along the tracks. The wheels are mounted inside the bottom of the walls and supported by the exterior sheet of 26-gauge galvanized steel on the PermaTherm wall panels, as well as the 18-gauge aluminum U-channel. Since there is space between the supports and the wheel (as shown in Figure 53), this pin experiences 3 point bending. The pin diameter is limited by the inner diameter of the wheel.

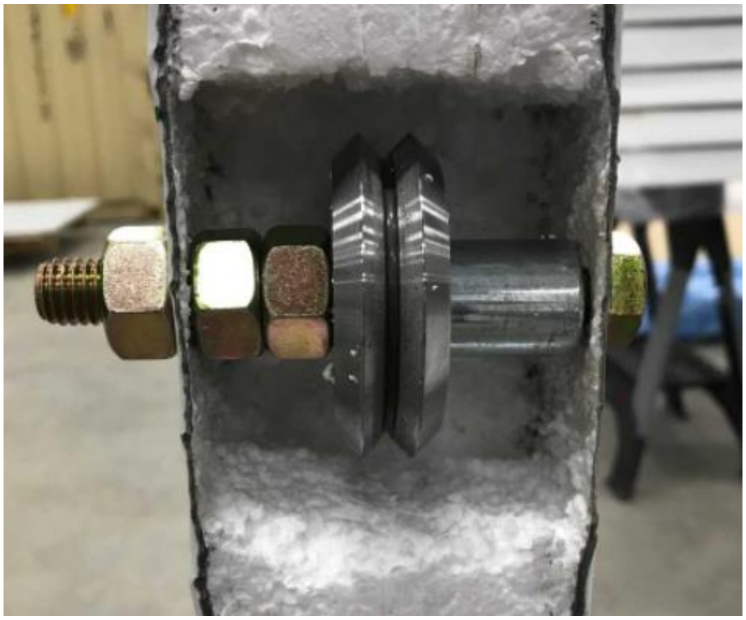


Figure 53: V-Wheel installation within PermaTherm wall panel

To determine the maximum stress experienced by the pin, the team determined the maximum moment and used the bending stress equation:

$$\sigma_{bend} = M_{bend} * \frac{c}{I_{bend}}$$

Where σ_{bend} is the bending stress (psi), M_{bend} is the moment (lbf-in), c is the distance from the neutral axis (in), and I_{pin} is the second moment of inertia (in^4). The stress was then compared with the yield strength for various materials to determine the safety factor for that material. The maximum stress was determined to be 3.115 kpsi, meaning steel had safety factor of 18.6. Since steel is a common material for bolts and relatively inexpensive, the team confirmed that a 9/16 in. steel shoulder bolt would be the best option. The full calculations can be found in Appendix B.

6.2.3 Pins – Locking Mechanism

The semi-collapsible unit is able to slide back and forth freely on the tracks. When the structure is in use, the compartments must be locked into position. This was achieved by bolting the back walls to a steel L-bracket attached to the floor as shown in Figure 54 below.

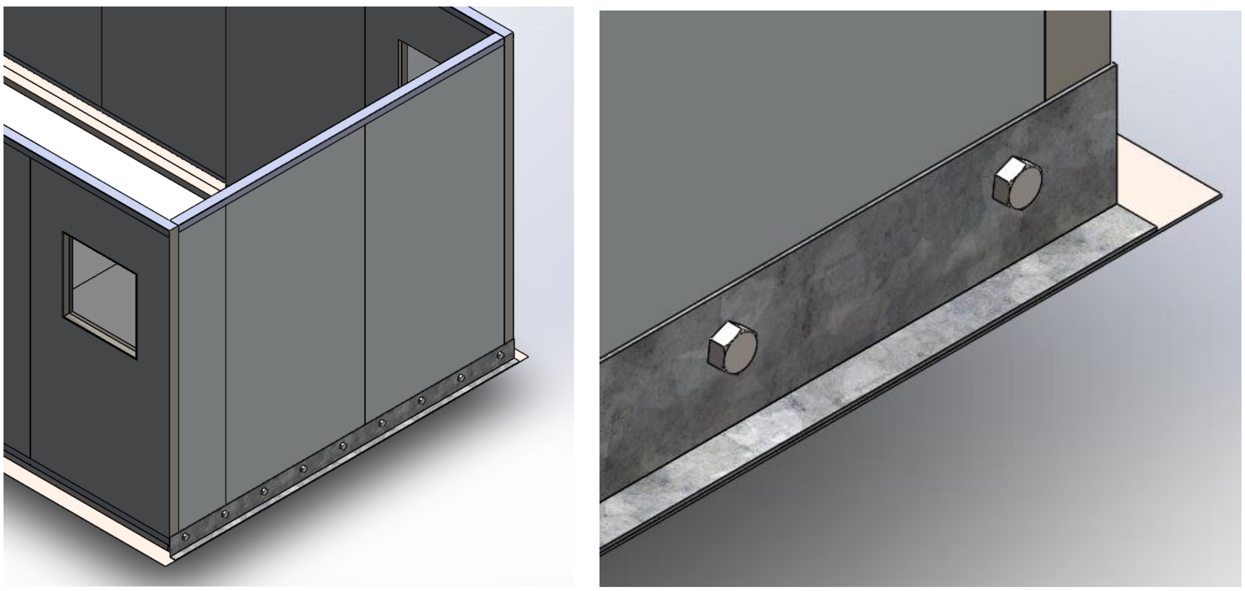


Figure 54: Locking mechanism

The exterior walls can be subjected to a variety of forces including hurricane force winds and the bolts must be able to withstand these forces. To calculate the forces experienced under such conditions, the force from the wind is divided by the number of bolts. The axial stress is then calculated using the equation:

$$\sigma_t = \frac{F_b}{A}$$

Where σ_t is the axial stress (psi), F_b is the force experienced by one bolt (lbf), and A is the cross-sectional area of the pin (in^2). When using nine 0.25 in. bolts, the safety factor for each bolt is 5.5. The full calculations can be found in Appendix E.

6.3 Fatigue Analysis and Fracture Mechanics

6.3.1 Modified Goodman Diagram Method

The erratic loading of the wind on a non-rotating product presents a challenge when predicting failure from fatigue. Full-scale physical testing is the ideal approach to determine the expected life of the unit. Based on the scope of this project, a combination of the Stress-Life (SN) approach and Linear Elastic Fracture Mechanics (LEFM) was used to estimate the expected life of the structure (Norton, 2014).

The point examined for the fatigue analysis is on the inside of the wall at the corner of a window, as shown by the blue dot in Figure 55. This point was selected because it experiences the highest tensile stress found in FEA models and crack propagation, the cause of fatigue failure, occurs in tension. The values for the mean (4.58 MPa) and alternating (49.56 MPa) stress components were taken from the Finite Element Analysis detailed in previous sections. The mean stress values are for the wall under no wind loading. The alternating stress values represent when the wall is loaded under the indicated wind load. Compressive forces are indicated by negative values and tensile forces are positive.

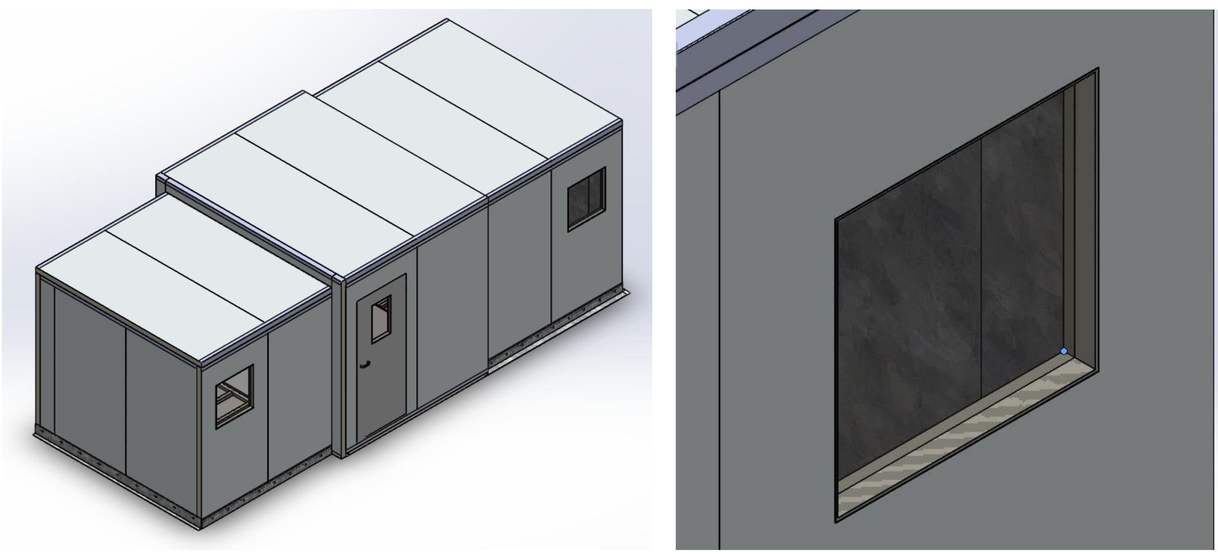


Figure 55: Point of interest for fatigue analysis

An excel sheet was developed for the fatigue analysis. Screenshots of the full spreadsheet can be found in Appendix H. Figure 56 depicts the materials correction factors for all of the analyses performed in this section.

Select Load Type			Fatigue Limit	Ultimate Strength	
Bending		Standard Value	225	450	Mpa
Select Size Parameters		Load Correction	1	1	
Rectangular Cross Sections		Size Correction	0.6	0.6	
in		Surface Correction	0.85	0.85	
Enter Diameter		Temperature Correction	1	1	
6		Reliability Correction	0.753	0.753	
Enter A95	Equivalent Diameter	Corrected Value	86.40675	172.8135	Mpa
184	49.01110867				
Surface Type					
0.85		Typical Non-Cylindrical Cross Sections		A95	
Enter Temperature		Rectangle			
Farenheit		Height	80		
100		Width	46	184	
Select Desired Reliability					
99.9%					

Figure 56: Material Correction Factors (Norton, 2014)

Figure 57 shows inputs for calculating K_f, the overall stress concentration factor, which is used in each analysis.

Input fatigue Coefficient	1
Input Kt	1.7
Input Notch Sensitivity (q)	0.8

Figure 57: Stress Concentration Factors (Norton, 2014)

6.3.2 Results

Analyses were completed using the stress values caused by 110 mph, 146 mph, and 210 mph. A Modified Goodman Diagram and a safety factor (represented by N_f) was calculated for steel for each loading scenario with a constant mean stress and varying alternating stress using the following equation:

$$N_f = \frac{S_f}{\sigma_a}(1 - \frac{\sigma_m}{S_{ut}})$$

For loading scenarios in which the safety factor was less than 1, a Cycles-to-Failure was calculated using the following equations:

$$N = (\frac{\sigma_{rev\_eq}}{a})^{\frac{1}{b}}$$

$$a = \frac{(fS_{ut})^2}{S_e}$$

$$b = \frac{-1}{3}\log(\frac{fS_{ut}}{S_e})$$

$$\sigma_{rev\_eq} = \frac{\sigma_a}{1 - \frac{\sigma_m}{S_{ut}}}$$

Figure 58 shows the input values and individual Von-Mises stresses for both mean and alternating at 110 mph. Figure 59 shows the resulting Modified Goodman Diagram. The N value of 1.0715 predicts infinite life. This prediction is possible because of the “knee” that exists in the graph of stress versus number of cycles for steel. This phenomenon indicates that failure will never occur for sufficiently low stresses.

Mean Stresses		Alternating Stresses			Input Units		Von-Mises Stresses		
Normal					Mpa		Mean	4.576024	Mpa
x	-3	x	1.90E+01				Alternating	49.55805	Mpa
y	0	y	0						
z	0	z	0						
Shear									
x	-0.7	x	17						
y	0	y	0						
z	0	x	0						

Figure 58: Inputs and Von-Mises Stresses (110 mph)

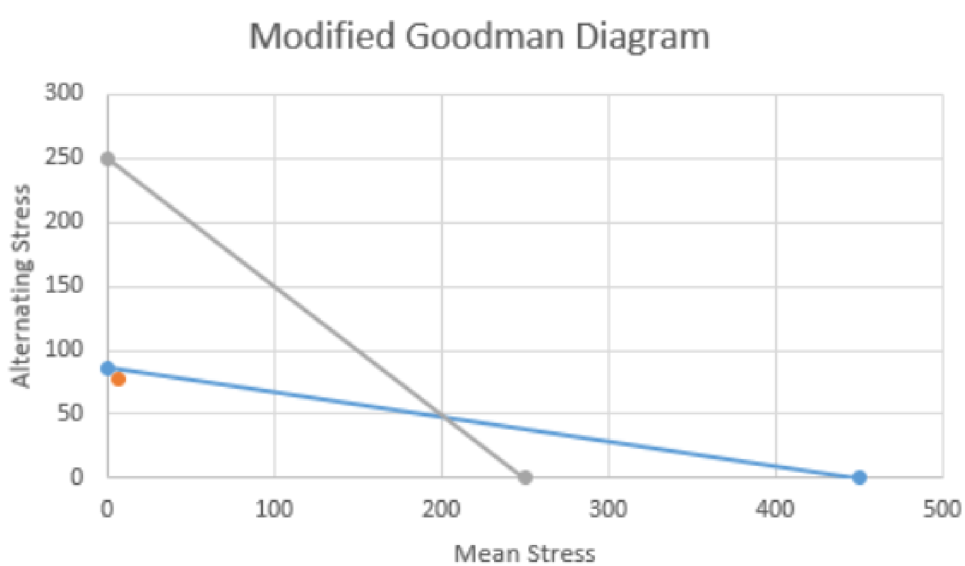


Figure 59: Modified Goodman Diagram [MPa] - 110 mph

Figure 60 shows the inputs and Von-Mises stresses for 146 mph. Figure 61 shows the Modified Goodman Diagram. This analysis predicts finite life with an N value of 0.5634. Figure 62 shows intermediate calculation values and a cycles-to-failure value of 3288.

Mean Stresses		Alternating Stresses			Input Units		Von-Mises Stresses		
Normal					Mpa		Mean	4.576024	Mpa
x	-3	x	3.70E+01				Alternating	94.24436	Mpa
y	0	y	0						
z	0	z	0						
Shear									
x	-0.7	x	32						
y	0	y	0						
z	0	x	0						

Figure 60: Inputs and Von-Mises Stresses (146 mph)

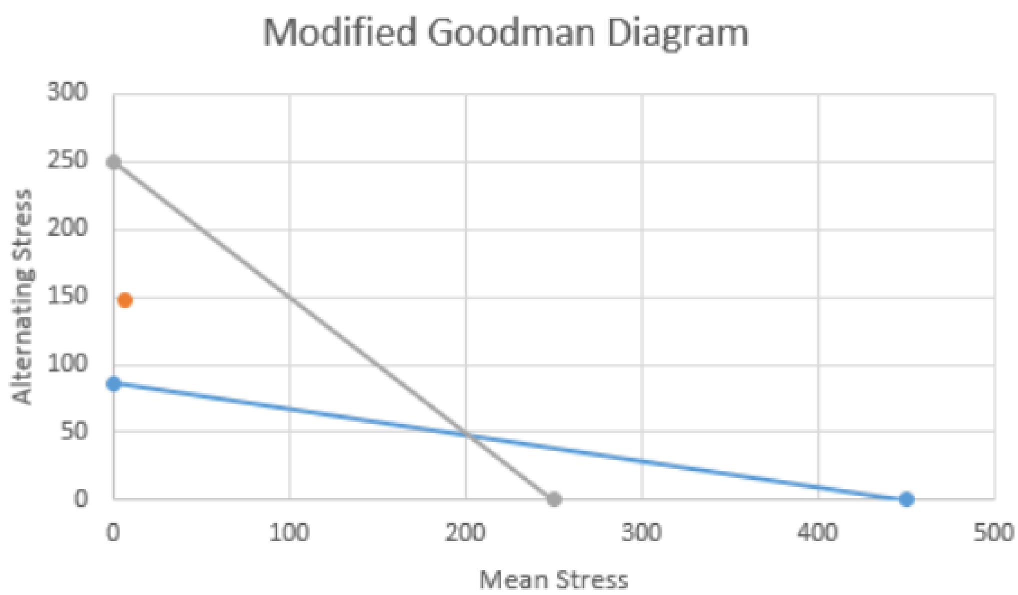


Figure 61: Modified Goodman Diagram [MPa] - 146 mph

a value	345.627
b value	-0.10034333
Reversible Equivalent	153.3560546
Cycles to Failure	3288.458697

Figure 62: Cycles to Failure Calculated Values - 146 mph

Figure 63 shows the inputs and Von-Mises stresses for 210 mph. Figure 64 shows the Modified Goodman Diagram, which returns an N value of 0.4515. Figure 65 presents the necessary values and cycles-to-failure value of 361, however, a value this low means that the S-N approach, intended for high-cycle applications, is not the best for this specific scenario. A Strain-Life approach or LEFM analysis would be more effective in this case. The same is true for the analysis of 253 mph, the results are not presented here they cannot be considered accurate, with a cycles-to-failure value of 2.8.

Mean Stresses		Alternating Stresses			Input Units		Von-Mises Stresses		
Normal					Mpa		Mean	4.576024	Mpa
x	-3	x	4.60E+01				Alternating	117.6095	Mpa
y	0	y	0						
z	0	z	0						
Shear									
x	-0.7	x	40						
y	0	y	0						
z	0	x	0						

Figure 63: Inputs and Von-Mises Stresses (210 mph)

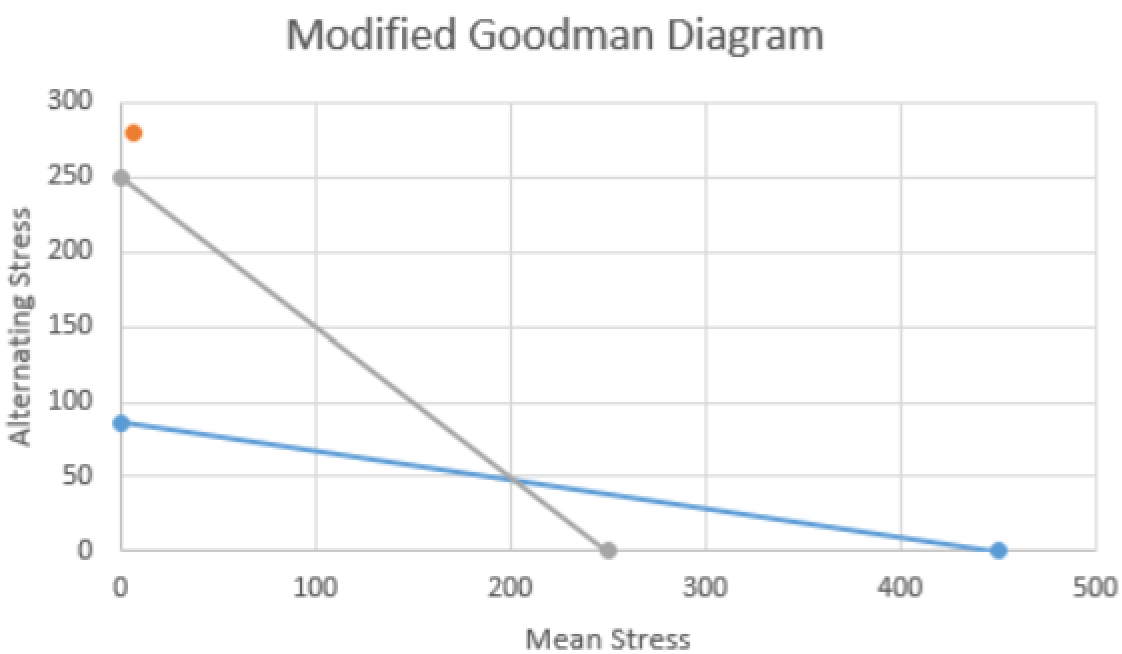


Figure 64: Modified Goodman Diagram [MPa] - 210 mph

a value	345.627
b value	-0.10034333
Reversible Equivalent	191.3762466
Cycles to Failure	361.7532529

Figure 65: Cycles to Failure Calculated Values - 210 mph

Chapter 7: Prototype Construction

7.1 Scaled Prototype

A 1:4 scale prototype of the model was created in an effort to predict design flaws when the full scale prototype was built. This prototype was built using plywood, fasteners, cabinet drawer tracks and door hinges. The scaled prototype costed about $200. The prototype was built to include a main compartment, and the small and medium compartments sliding out of both sides. Due to tolerance errors, the team was not able to create the small compartment. Figure 66 shows the scaled prototype.

Figure 66: 1:4 scale prototype

From the scaled prototype process, it was determined that the sliding track could not be mounted to the sides of the sliding compartments and must be mounted to floor studs to support the weight of the compartments. It was also found that the floor will need a mechanism to hold it up when the unit is in the collapsed position.

7.2 Full Scale Prototype

The full scale prototype was constructed at the Deployed Resources facility in Rome, NY. Deployed Resources employees assembled the floor framing based on detailed drawings provided by the WPI team (see Appendix I). The floor frame was built with steel and welded using MIG welding. Figure 67 displays the floor framing.

Figure 67: Assembled floor frame

The project team then constructed the wall and roof panels with assistance from Deployed Resources employees. The panels were assembled in accordance with the instructions provided by PermaTherm. The team first assembled the medium compartment which had three V-track wheels and three float wheels recessed into the bottom of the walls. Figure 68 depicts the V-track wheel assembly.

Figure 68: V-Track wheel assembly

Once each individual wall section was built, they were connected using the tongue and groove joint, caulk, and U-channels at the top and bottom of the panels. Fasteners were placed 8 in. on center along the tongue and groove seams and the U-channels. Wall sections were connected at corners using L-brackets. Figure 69 shows the medium compartment wall and roof assembly.

Figure 69: Medium compartment wall and roof assembly

Once the medium section was complete, the small section was built. This section was assembled using the same process of the medium compartment and placed it on the tracks. Due to tight tolerances, this compartment did not seamlessly slide inside the medium compartment. The screw heads from the small section interfered with the screw heads from the medium section. Figure 70 exemplifies this issue.

Figure 70: Collision between small and medium sections

To resolve this issue, the team shortened the compartment by 1.5 inches. Though this solved the problem, the float bar was not wide enough the hold the entire width of the wheel. Though the wheel still rolled effectively, this was not an ideal situation and, in the future, would be mitigated by widening the float bar track.

With these two sections in place, The main compartment was built. C-channels were fastened directly the frame, and the wall pieces where then attached to the C-channels. The roof was placed on the wall panels last. Figure 71 shows the assembly of all three compartments.

Figure 71: Full unit collapsed (top left) full unit expanded (top right) Profile view of unit collapsed (bottom)

The most significant finding after designing the full-scale prototype was that although the track allowed for the rigid small and medium compartments to be fully expanded, the main section needed more rigidity. As this was an early stage prototype, the team did not have time to fabricate locking mechanisms, interior design work, windows, or doors. With these features in place, the main section will show more rigidity when an external force is applied to an outer wall face.

Chapter 8: Conclusions and Recommendations

Through research, design, analysis, and prototyping, this project provided Deployed Resources with a new and innovative design concept. Unlike the current systems that fully collapse, or do not collapse at all, this design allows for five units to be shipped on a truck with bathroom and kitchen features already installed. Upon delivery, minimal effort would be required to prepare the unit for use. The full scale prototype helped to validate the structural integrity of the unit as calculated by the analysis methods in Chapter 6. It also confirmed that a wheels and track system can be effectively employed to expand and collapse a multi-compartment temporary housing unit. The full scale prototype helped the team identify flaws in the design which could be improved in future design iterations. Deployed Resources will have the opportunity to improve upon the design now that this project is completed. During creation of the prototype, Deployed Resources reported that they found it easier to create a design from scratch based on drawings, rather than re-constructing a shipping container. To advance the current prototype into a marketable product, the team offers Deployed Resources the following recommendations for future work on the design:

- Pursue a composite material for the floor frame that is more lightweight than steel but stronger than aluminum. This may not be achievable based on monetary constraints.
- Pursue a more cost-effective material for the subfloor that is as strong and lightweight as Coosa Board and offers the same resistance to mold. Currently, Coosa Board accounts for a larger percentage of the unit cost than is preferable.
- Test researched methods to seal all openings between sections of the unit. The team could not test weatherproofing material for this purpose within the time constraints of the project.
- Test the locking mechanism discussed in Section 5.2.7. The team could not test the L-bracket locking mechanism within the time constraints of the project.
- Develop a mechanism to secure the floors once they have been folded to the upright position.
- Install only two V-track wheels and two float wheels for each sliding compartment. During the prototyping phase, three of each wheel were used but the middle wheel did not provide additional strength or smoothness to the system when compared to a two-wheel design. Based on calculations in Appendix B, a 3-wheel design has a safety factor of 18.6 for bending of the wheel axle. The calculations were repeated using a 2-wheel design resulting in a safety factor of 12.4.
- Widen the float wheel track to allow for a greater margin of error when connecting the sliding compartments to the floor frame. A narrow float wheel track may result in the float wheel overhanging the edge of the track when installed.

- Design for more than 0.25 in. tolerance between sliding sections. Due to field cut errors, this tolerance level resulted in collisions between compartments during prototype construction.
- Use a float wheel that can be mounted using a through hole in a similar fashion as the V-wheels. The cantilevered design used in the prototype resulted in greater stresses than the 3-point bending orientation of the V-wheels.

Though the design was originally intended for hurricane relief, this product could also be used in conjunction with Deployed Resources current products for event management and pop-up short term living.

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Appendix A: Failure Modes & Effects Analysis (FMEA)

Occurrence: This criterion refers to how likely a failure is to take place. An occurrence score was determined based on how developed this specific function or process involved was, and what analytical test data was available to suggest adequate safety factors. A failure would receive a 4 if it does not depend on a failure of a system or component and is anticipated to occur during the lifetime of the unit. A 3 would represent a failure that may be expected to occur at some point during the lifetime of the unit, but that would require a failure of a system or component. A 2 indicates that a failure that is possible, but that would require a system failure that is extremely unlikely. A 1 represents a failure that would result from system failures that are beyond extremely unlikely to occur (Yung, 2008).

Severity: This criterion refers to the impact of a failure. A severity score was determined based on the nature of the failure, and research on similar failures in other settings and the resulting consequences. A severity of 4 represents occupant endangerment or death. A 3 suggests the unit is no longer habitable or restorable, but that lives will not be at risk due to the failure. A 2 indicates reparable damage to the unit in which the unit needs restorations before continued use. A 1 represents a failure resulting in only minor damage to the unit.

Function/Process	Potential Failure Mode	Potential Effect of Faliure	Severity (1-4)	Potential Cause of Faliure	Occurrence (1-4)	Hazard Score	Critical Analysis
Walls and Ceiling	walls or ceiling cave in	Housing unit is destroyed, lives are at risk	4	Forces are too strong	1	4	Doesn't need to change
Gap Sealant	gap closing methods are not perfect and water leakes in	materials are ruined by water damage	2	not enough pressure on gaskets	3	6	Needs to Change
Plumbing and Electricity	There is not enough room for these systems during build	The structure is not habitable, needs to be re designed	4	not properly engineered	1	4	Doesn't need to change
Roof	too much water builds up on roof	Water leaks into system or runs off along windows and doors	2	flat roof	3	6	Needs to Change
Feet and leveling system	Feet buckle under weight and break	floor is damaged	4	too much weight is put on the feet	2	8	Needs to Change
Track system	Sliding walls get knocked off the track	housing unit will be compromised, lives are at risk	4	Unexpected force on walls, track is not straight	3	12	Needs to Change
Structure	Unit tips over in expanded	Housing unit destroyed, loss of life	4	wind force is greater than COM force	2	8	Needs to Change
Structure	Unit struck by lightning	People shocked by lightning	4	Not properly grounded	1	4	Doesn't need to change
Floor folding down	Floor Fold down and hit someone	Personal Injury	3	Floor is too heavy	2	6	Needs to Change
Walls sliding out	Pinched by walls wile expanding	Personal Injury	1	Not paying attention	2	2	Doesn't need to change
Strucutre	Too much/too loud of noise inside unit	Loud/Uncomfortable living situation	2	Unit made of metal	4	8	Needs to Change
kitchen	Hot plate starts a fire	damage to unit, life at risk	3	Personal mistake	1	3	Doesn't need to change
Floor folding down	Trip over hinges	Personal injury	1	Hinge is raised above the floor	2	2	Doesn't need to change
Walls sliding out	unable to pull out sides	personal injury, un able to pull out	1	unit is too hevy	2	2	Doesn't need to change
Walls Slidng out	Locking mechanism breaks	walls dont stay extende	2	too much force on the locking mechanism	2	4	Doesn't need to change
floor folding down	Hinges snap	Floors fall off	1	angle increased past hinge	1	1	Doesn't need to change

Appendix B: Hand Calculations: Pins - Wheels

Wheel Axle Calculations

Dimensions

Pin diameter $D_p := .563in$

wheel thickness $t_{wh} := 0.75in$

Pin Area $A_{pin} := \frac{\pi}{4} \cdot D_p^{\,2} = 0.249 \cdot in^2$

Steel Wall thickness $t_{st} := 0.01875 \cdot in$

Steel Yield Strength $y_{sh} := 400MPa = 5.802 \times 10^4\ psi$

Length of Pin $L := 3in = 3 \cdot in$

Forces Seem on the Axle

Weight of the wall $F_w := 126.3lb \cdot 32 \frac{ft}{s^2} = 125.617 \cdot lbf$

$F_{total} := F_w \cdot \frac{4}{6}$

# of walls/
#of wheels

3 point bending calculations

Maximum moment $M_{bend} := F_{total} \cdot \frac{L}{4} = 62.808 \cdot lbf \cdot in$

Distance of stress element from neutral axis $c := \frac{D_p}{2} = 0.281 \cdot in$

Moment of Inertia $I_{pin} := \frac{\pi}{4} \cdot c^4 = 4.932 \times 10^{-3} \cdot in^4$

Bending Stress $\sigma_{bend} := M_{bend} \cdot \frac{c}{I_{pin}} = 3.585 \times 10^3\ psi$

Safety Factor $\boxed{SF := \frac{y_{sh}}{\sigma_{bend}} = 16.183}$

Appendix C: Buckling Calculations for the Leveling Feet

Buckling of Leveling Feet

The feet are mounted on the floor frame and height can be adjusted by the nut it threads into. This provides support for the floors once they are folded down and acts as a way to level the structure.

$l := 10in = 254 \cdot mm$ $\quad d := 1in = 25.4 \cdot mm$ $\quad E := 180GPa$

For our design, the bolt is 10 in. long (254 mm), has a diameter of 1 in. (25.4 mm), and is made ou of stainless steel.

Area moment of inertia	Area	Radius of gyration	Slenderness Ratio
$I := \frac{\pi \cdot (d^4)}{64} = 2.043 \times 10^4 \cdot mm^4$	$A := \frac{\pi}{4} \cdot d^2 = 506.707 \cdot mm^2$	$k := \sqrt{\frac{I}{A}} = 6.35 \cdot mm$	$S_r := \frac{l}{k} = 40$

Since the Slenderness Ratio above is greater than 10, this is considered a long column and would fail due to buckling.

The formula for the critical load that this column will fail is listed below

$$P_{cr} := \frac{A \cdot \pi^2 \cdot E}{S_r^2} = 562.613 \cdot kN$$

Must find the effective length which is determined by the boundary conditions of the column. The boundary conditions of the leveling feet are Fixed-Pinned since the base allows for rotation and the top is threaded into a nut welded to the floor. This can be used to calculate a new Slenderness Ratio.

$L_{eff} := 0.8l$ $\qquad S_{reff} := \frac{L_{eff}}{k}$

English units

$P_{creff} := \frac{A \cdot \pi^2 \cdot E}{S_{reff}^2} = 879.082 \cdot kN$ $\qquad P_{creff} = 1.976 \times 10^5 \cdot lbf$

Therefore the load each of these bolts would have to take is conservatively 562.6 kN or 197,000 lbf.

Our floor weighs approximately 1000 lbs and is split between two of these feet and the hinges connecting it to the main compartment

Appendix D: Specification Sheets for Purchased Materials

PermaTherm Panels:

EPS Physical Properties

Physical Properties	ASTM Method	Units	1 lb Density	2 lb Density
Density, Minimum	D1622	lb/ft^3	0.9	1.8
Density, as tested	D1622	lb/ft^3	1.0	2.0
Density, Range	D1622	lb/ft^3	0.9-1.14	1.8-2.2
Compressive Strength	D1621	lb/in^2	10-24	25-33
Shear Strength	C273	lb/in^2	18-22	33-37
Shear Modulus	C273	lb/in^2	280-320	600-640
Modulus of Elasticity	C273	lb/in^2	180-220	460-500
Tensile Strength	D1623	lb/in^2	16-20	23-27
Flexural Strength	C203	lb/in^2	25-30	50-75
Thermal Conductivity: K-Factor @1"	C177/C518	BTU-in/hr-ft^2-F		
@ 25F (-3.9C)			0.23	0.20
@ 40F (4.4C)			0.24	0.21
@ 75F (43.3C)			0.26	0.23
Thermal Resistance: R-Factor @1"	C177/C518	hr-ft^2-F/BTU		
@ 25F (-3.9C)			4.35	5.00
@ 40F (4.4C)			4.17	4.76
@ 75F (43.3C)			3.85	4.35
Water Absorption	C272	%	<4.0	<2.0
Water Vapor Transmission	E96	perm-inch	2.0-5.0	0.6-2.0
Capillarity			None	None
Coefficient, Thermal Exp.	D696		0.000035	0.000035
Long Term Service Temp		F	167	167
Maximum Exposure Temp		F	180	180
Oxygen Index	D2863		24.0	24.0

Thermal Resistance (1 lb Density @ 40F)

Thickness (inches)	2	3	4	6	8	10	12
R-Value	8	13	17	25	33	42	50

Panel Manufacturing Tolerances

Length:
- Up to 20 feet: +/- 1/8 inch
- Over 20 feet: +/- 3/16 inch

Width:
- 32-48 inches: +/- 1/8 inch

Thickness:
- 2-12 inches: +/- 1/8 inch

Squareness: +/- 1/8 inch (measured 6 inches from end)

Lateral Bow:
- Up to 10 feet: +/- 3/32 inch
- 10 ft to 20 ft: +/- 3/16 inch
- Over 20 feet: +/- 3/8 inch

Flatness: +/- 3/16 inch per 2 foot span

Joints: Male/female joint edges flush, with no more than 1/8 inch deviation

Maximum Wall Spans for Uniform Loads

(Units in Feet for 26-Gauge Steel Panel Skins)

Core Thickness	Total Uniform Load (lb/sq ft) 5	10	20	30	40	50	60
2 inch	18	13	9	7	6	5	3
3 inch	22	16	10	9	6	5	4
4 inch	25	18	13	10	8	7	6
5 inch	30	22	15	12	9	8	7
6 inch	32	23	16	13	10	9	8
8 inch	36	25	19	15	12	11	10
10 inch	41	29	20	17	14	12	11

Surface Panel Burning Characteristics (1 lb Density)

	ASTM Method	UL Rating
Flame Spread @ 6"	E 84	0
Smoke Density @ 6"	E 84	100
Hot Surface	C 41	Pass

Coosa Board:

COOSA COMPOSITES, LLC

105 Pardue Road
Pelham, AL 35124
Phone: 205-663-3225
Fax: 205-663-4645

	Density ASTM C271	Core Shear ASTM C273		Core Compressive ASTM C365		Flatwise Tensile ASTM C297	Flexural Properties ASTM D790	
		Strength	Modulus	Strength	Modulus	Strength	Strength	Modulus
	(lb/ft^3) / (kg/m^3)	(psi) / (MPa)	(psi) / (MPa)	(psi) / (MPa)	(psi) / (MPa)	(psi) / (MPa)	(psi) / (MPa)	(psi) / (MPa)
Bluewater 20								
0.50" / 12 mm	20 / 320	410 / 2.83	3,640 / 25.10	510 / 3.52	9,150 / 63.09	380 / 2.62	3,860 / 26.61	188,700 / 1,301.04
0.75" / 20 mm	20 / 320	420 / 2.90	4,660 / 32.13	410 / 2.83	7,270 / 50.12	440 / 3.03	2,830 / 19.51	166,000 / 1,144.53
1.50'" / 38 mm	20 / 320	500 / 3.45	6,360 / 43.65	660 / 4.55	19,460 / 134.17	570 / 3.93	2,750 / 18.96	135,000 / 930.79
Bluewater 26								
0.50" / 12 mm	26 /416	550 / 3.79	2,050 / 14.13	800 / 5.52	13,980 / 96.39	690 / 4.76	5,260 / 36.27	265,300 / 1,829.18
0.75" / 20 mm	26 / 416	530 / 3.65	4,220 / 29.10	820 / 5.65	11,810 / 81.43	480 / 3.31	4,9.60 / 34.20	242,900 / 1,674.74
1.50" / 38 mm	26 / 416	520 / 3.59	6,300 / 43.44	1,060 / 7.31	31,050 / 214.08	510 / 3.52	4,010 / 27.65	215,100 / 1,483.06
Nautical 15								
0.50" / 12 mm	15 / 240	410 / 2.83	2,680 / 18.48	400 / 2.76	7,130 / 49.16	340 / 2.34	2,220 / 15.31	83,900 / 578.47
Nautical 20								
0.50" / 12 mm	20 / 320	450 / 3.10	2,970 / 20.48	600 / 4.14	13,340 / 91.98	600 / 4.14	2,700 / 18.62	91,700 / 632.25
0.75" / 20 mm	20 / 320	510 / 3.52	3,740 / 25.79	740 / 5.10	15,710 / 108.32	630 / 4.34	2,430 / 16.75	71,800 / 495.04
1.50" / 38 mm	20 / 320	420 / 2.90	5,220 / 35.99	530 / 3.65	19,339 / 133.34	420 / 2.90	2,310 / 15.93	75,200 / 518.49
Nautical 24								
0.50" / 12 mm	24 / 384	650 / 4.48	3,990 / 27.51	980 / 6.76	16,830 / 116.04	550 / 3.79	3,430 / 23.65	114,700 / 790.33
0.75" / 20 mm	24 / 384	630 / 4.34	5,630 / 38.82	630 / 4.34	9,330 / 64.33	660 / 4.55	2,910 / 20.06	99,100 / 683.27

*ASTM D790 - 3 point Bending, L/d=16/1

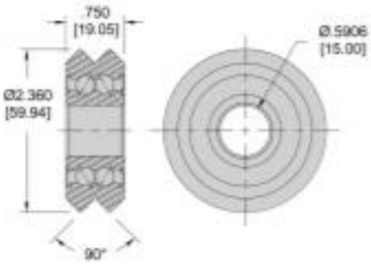
Important! The information and data presented herein are based upon information reasonably available to Coosa Composites, LLC from independent testing labs at the time of publication and are presented in good faith, but are not to be construed as guarantees or warranties, express or implied, regarding performance, results are to be obtained from use, comprehensiveness, and merchantability. You should thoroughly test any application, and independently determine satisfactory performance before commercialization or use.

Revised April 2012

Bishop Wisecarver V-Wheels and Track:

Size 4

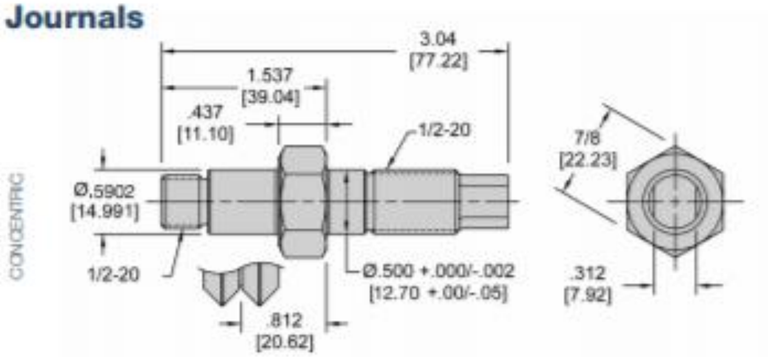
Wheels — Original

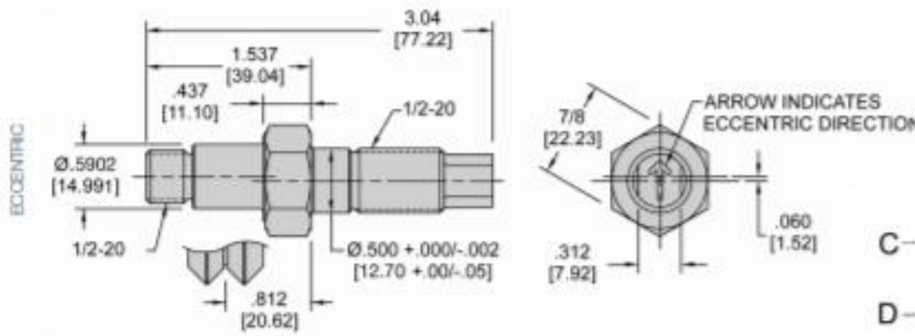


STOCK CODE	MATERIAL	PROTECTION	WEIGHT (g)	TEMPERATURE RANGE	LOAD RATINGS (lbf)	
					AXIAL	RADIAL
				DEGREES F	L_A	L_R
W4X	52100 Steel	Seal shield	276	-22° to +212°	900	2181
W4SSX	440C Stainless	Seal shield		-22° to +212°	900	2181
W4SS227	440C Stainless	Shield		-22° to +500°	747	1810
W4SS300	440C Stainless	Shield		-94° to +230°	747	1810

NOTE: To convert lbf to Newtons, multiply by 4.448
To convert inches to millimeters, multiply by 25.4

Journals





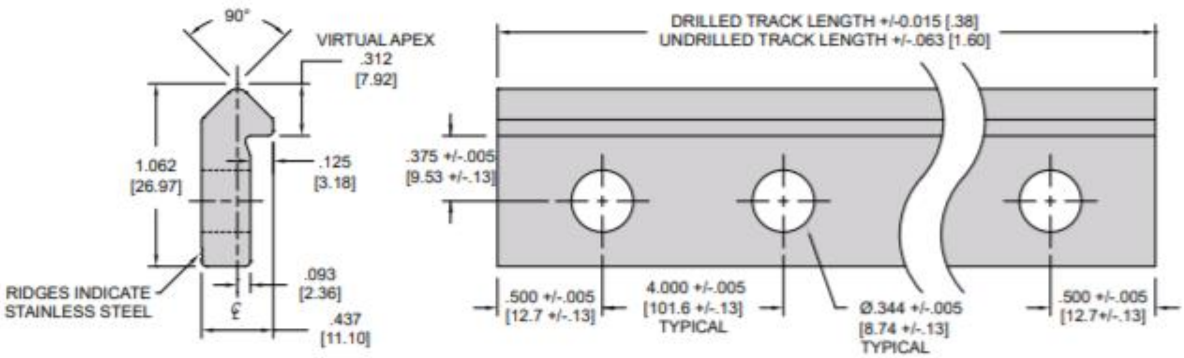
STOCK CODE	STYLE	WEIGHT (g)	WHEEL MOUNTING SIDE			JOURNAL MOUNTING SIDE			
			MOUNTING SURFACE TO WHEEL VEE	WHEEL MOUNTING NUT	WHEEL MOUNTING WASHER	JOURNAL MOUNTING WASHER	JOURNAL MOUNTING NUT	MIN. MOUNTING PLATE THICKNESS	MAX. MOUNTING PLATE THICKNESS
				A	B	C	D		
MJC4A	Concentric	133.1	.812	1/2-20 Zinc plated Nylon locking	1/2 Flat washer stainless steel	1/2 Flat washer stainless steel	1/2-20 Zinc plated Nylon locking	.375	.750
MJX4A	Eccentric								

Values are in inches
Journal material is AISI 303 stainless steel
Supplied with mounting nut and washer, without guide wheel

Bishop-Wisecarver 29

Size 4

Track



STOCK CODE PREFIX	MATERIAL	DESCRIPTION	HARDNESS	MAXIMUM LENGTH (ft)	WEIGHT (lbs./ft)	FINISHING
T4-	1045 Carbon	Hardened	HRC 53 min.	20	1.100	Polished & oiled
TS4-		Soft	HRC 22-25	22		
T4SS-	420 Stainless	Hardened	HRC 40 min.	20		
TS4SS-		Soft	HRC 20-22	22		

Track without holes available by the foot

Hardened track is induction hardened and polished on the vee surfaces

STOCK CODES				STANDARD LENGTHS (in)	# OF HOLES
1045 CARBON STEEL		420 STAINLESS STEEL			
HARDENED	SOFT	HARDENED	SOFT		
T4-1300-4	TS4-1300-4	T4SS-1300-4	TS4SS-1300-4	13.00	4
T4-2500-7	TS4-2500-7	T4SS-2500-7	TS4SS-2500-7	25.00	7
T4-3700-10	TS4-3700-10	T4SS-3700-10	TS4SS-3700-10	37.00	10
T4-4900-13	TS4-4900-13	T4SS-4900-13	TS4SS-4900-13	49.00	13
T4-6100-16	TS4-6100-16	T4SS-6100-16	TS4SS-6100-16	61.00	16
T4-7300-19	TS4-7300-19	T4SS-7300-19	TS4SS-7300-19	73.00	19

Available undrilled by the foot. Length cut tolerance of undrilled track is +/-0.063 [1.60]

Available made-to-order with user specified length, hole spacing, and machining

McMaster-Carr Leveling Feet:

Swivel Leveling Mount

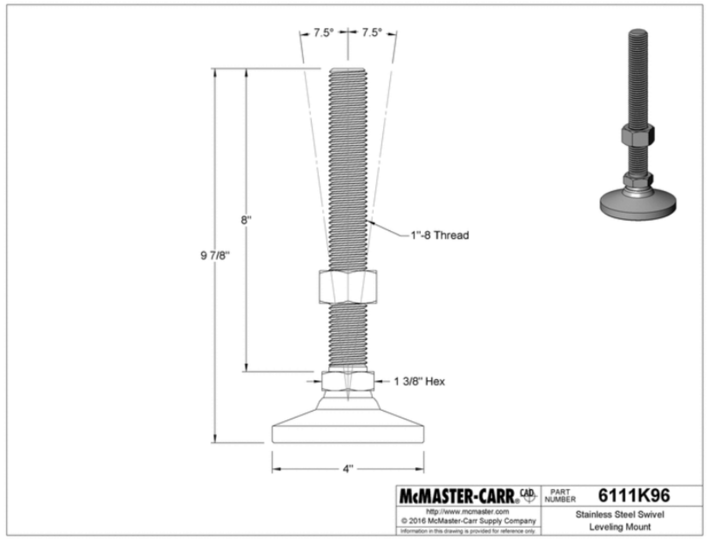
Corrosion-Resistant 303 Stainless Steel with 8" Long 1"-8 Threaded Stud

Each | ADD TO ORDER

In stock
$77.40 Each
6111K96

Adjustability	Swivel
Mount Type	Threaded Stud
Thread Size	1"-8
Thread Type	UNC
Thread Length	8"
Capacity per Mount	20,000 lbs.
Swivel Range of Motion	7.5°
Base Diameter	4"
Overall Height	9 7/8"
Hex Nut Width	1 3/8"
Base Shape	Round
Base Material	303 Stainless Steel
Stud Material	303 Stainless Steel
Hex Nut Material	303 Stainless Steel
Includes	Locknut
RoHS	Compliant

Made entirely of stainless steel, these mounts resist corrosion from water and most chemicals. Their ball-and-socket design swivels to compensate for uneven floors. In addition to leveling, mounts raise equipment off the floor for easier cleaning and inspection.

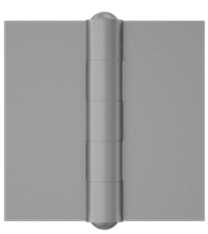


The information in this 3-D model is provided for reference only. Details

McMaster-Carr Hinges:

Unfinished Steel Surface-Mount Hinge

Nonremovable Pin, 4" x 2" Door Leaf, 0.180" Leaf Thickness

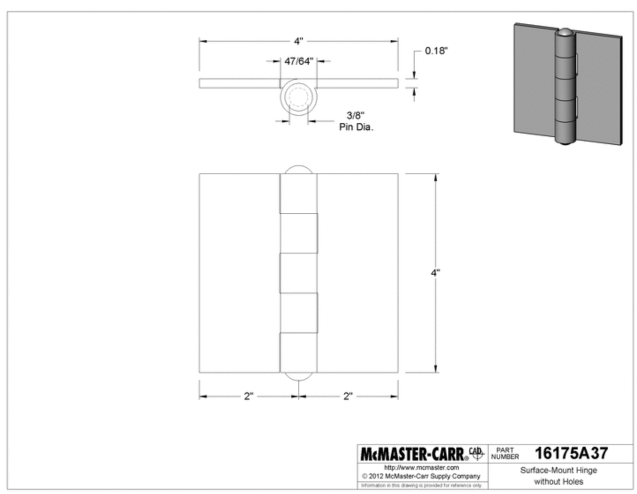


Each | ADD TO ORDER

In stock
1-9 Each $10.03
10 or more $8.02
16175A37

Hinge Type	Butt
Mounting Style	Surface
Mounting Holes	Without Holes
Opening/Closing Action	Standard
Material	Unfinished Steel
Appearance	Dull
Door Leaf	
Height	4"
Width	2"
Frame Leaf	
Height	4"
Width	2"
Overall Width	4"
Leaf Thickness	0.180"
Range of Motion	265°
Capacity	Not Rated
Pin Type	Nonremovable
Pin Diameter	3/8"
Pin Material	Steel
Mount Type	Screw-On, Weld-On
Door Mounting Location	Left Side, Right Side
RoHS	Compliant

Hinges with a nonremovable pin deter tampering.



The information in this 3-D model is provided for reference only. Details

Appendix E: Hand Calculations: Pins – Locking Mechanism

Back Bolt

$Ac := 10ft \cdot 8ft = 1.152 \times 10^{4}$ $V_{windc} := 160 \dfrac{mile}{hr}$ $P := V_{windc}{}^{2} \cdot 0.00256 \dfrac{hr^{2} \cdot lbf}{(mile \cdot ft)^{2}} = 65.536 \cdot \dfrac{lbf}{ft^{2}}$

F_{windc} Wind Force $F_{windc} := Ac \cdot P = 5.243 \times 10^{3}\ lbf$

D_p Pin diameter $D_p := .25in$ $A := D_p{}^{2} \cdot \dfrac{\pi}{4} = 0.049\ in^{2}$

Distributed force over # bolts $F_b := \dfrac{F_{windc}}{9}$ $\sigma_t := \dfrac{F_b}{A} = 1.187 \times 10^{4}\ psi$ $y_{ten} := 65000psi$

$$\boxed{SF := \frac{y_{ten}}{\sigma_t} = 5.477}$$

Appendix F: Finite Element Analysis (FEA) Method Verification through Hand Calculations

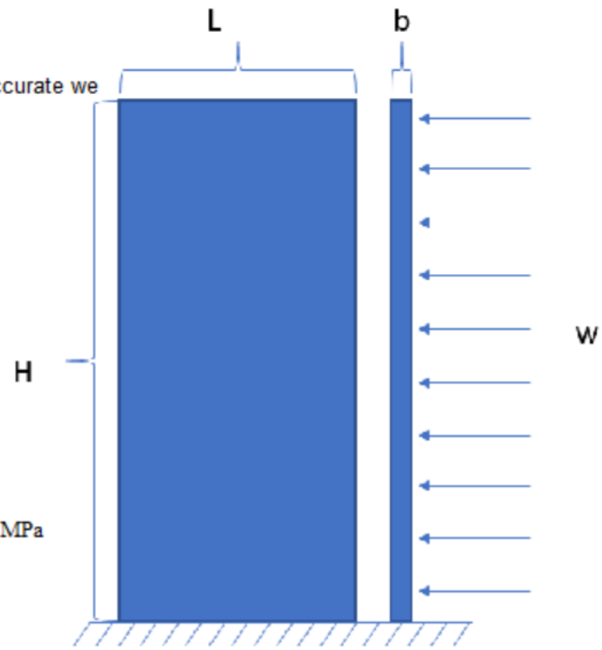
Wall Deflection

ANSYS Simplified Model Check

Cantilevered wall - Uniformly distributed load

To verify that the results we got from ANSYS were accurate we ran this simplified model to compare it to.

The dimensions of the panel



Height of wall $h := 8\text{ft} = 2.438\,\text{m}$

Thickness of wall $b := 1\text{in} = 0.025\cdot\text{m}$

Length of wall $l := 4\text{ft} = 1.219\,\text{m}$

Area $A_1 := b\cdot l = 0.031\cdot\text{m}^2$

Volume of panel $V_{wall} := h\cdot l\cdot b = 0.076\cdot\text{m}^3$

Elastic Modulus $E := 2.9008\cdot 10^7\,\text{psi} = 2\times 10^5\cdot\text{MPa}$

Density of Steel $\rho_{steel} := 7850\,\dfrac{\text{kg}}{\text{m}^3}$

The distributed load comes from the pressure on the panel due to the wind

$w := 58.3\text{psf}\cdot 4\text{ft} = 233.2\,\dfrac{1}{\text{ft}}\cdot\text{lbf}$ along the height

$F_{wind} := w\cdot h = 8.299\times 10^3\cdot\text{N}$

$M := F_{wind}\cdot\dfrac{h}{2} = 1.012\times 10^4\cdot\text{N}\cdot\text{m}$ Moment of Intertia $I := \dfrac{b^3\cdot l}{12} = 1.929\times 10^{-4}\cdot\text{ft}^4$

Deflection

$$d := \frac{w\cdot h^4}{8\cdot E\cdot I} = 45.165\cdot\text{mm}$$

Stresses at the base of the wall

Axial Compression

$F_w := \rho_{steel}\cdot V_{wall}\cdot g = 5.813\cdot\text{kN}$

$\sigma_w := \dfrac{F_w}{A_1} = 0.188\cdot\text{MPa}$

Compression / Tension due to bending

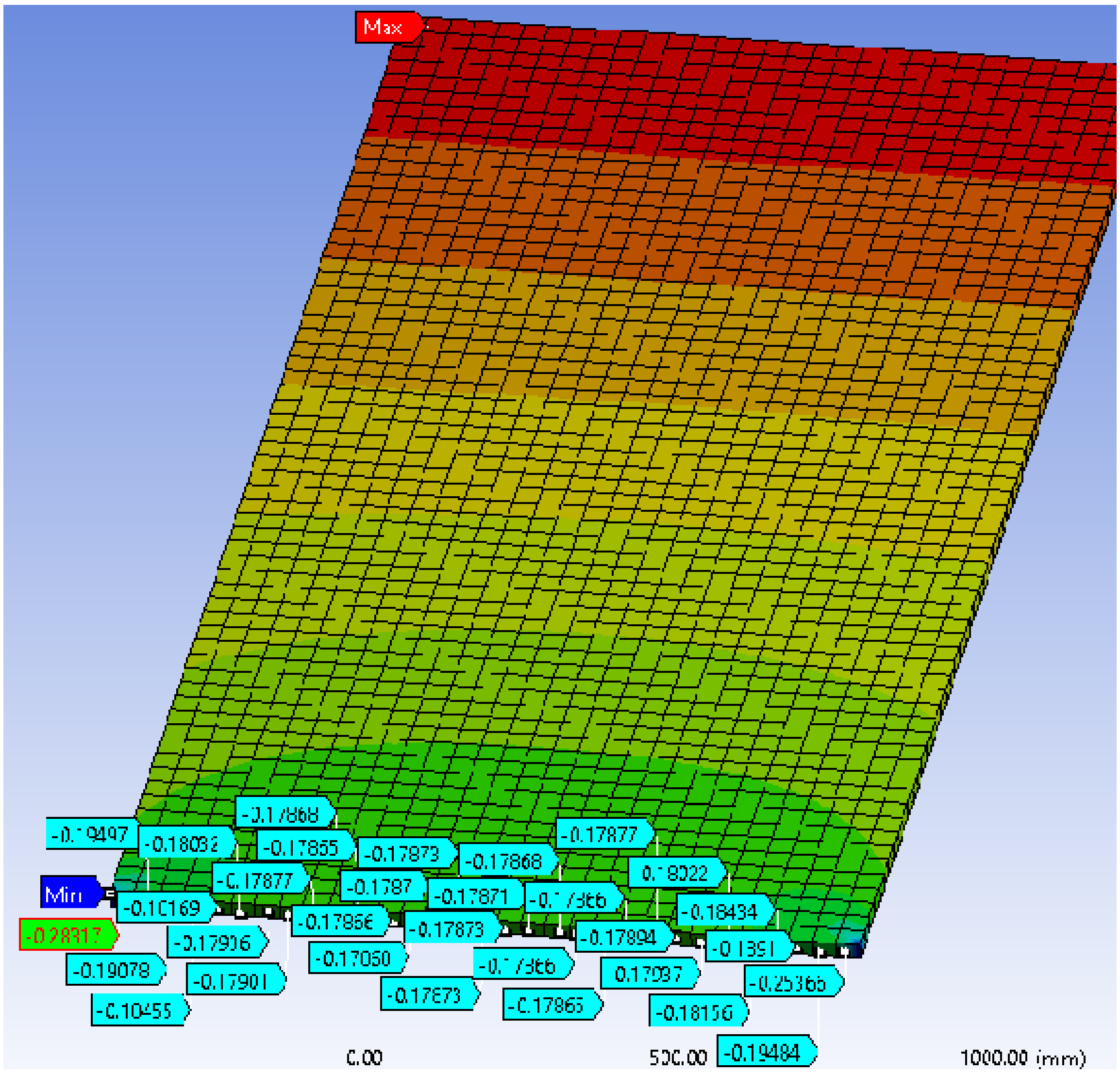
$c := \dfrac{b}{2} = 0.042\,\text{ft}$

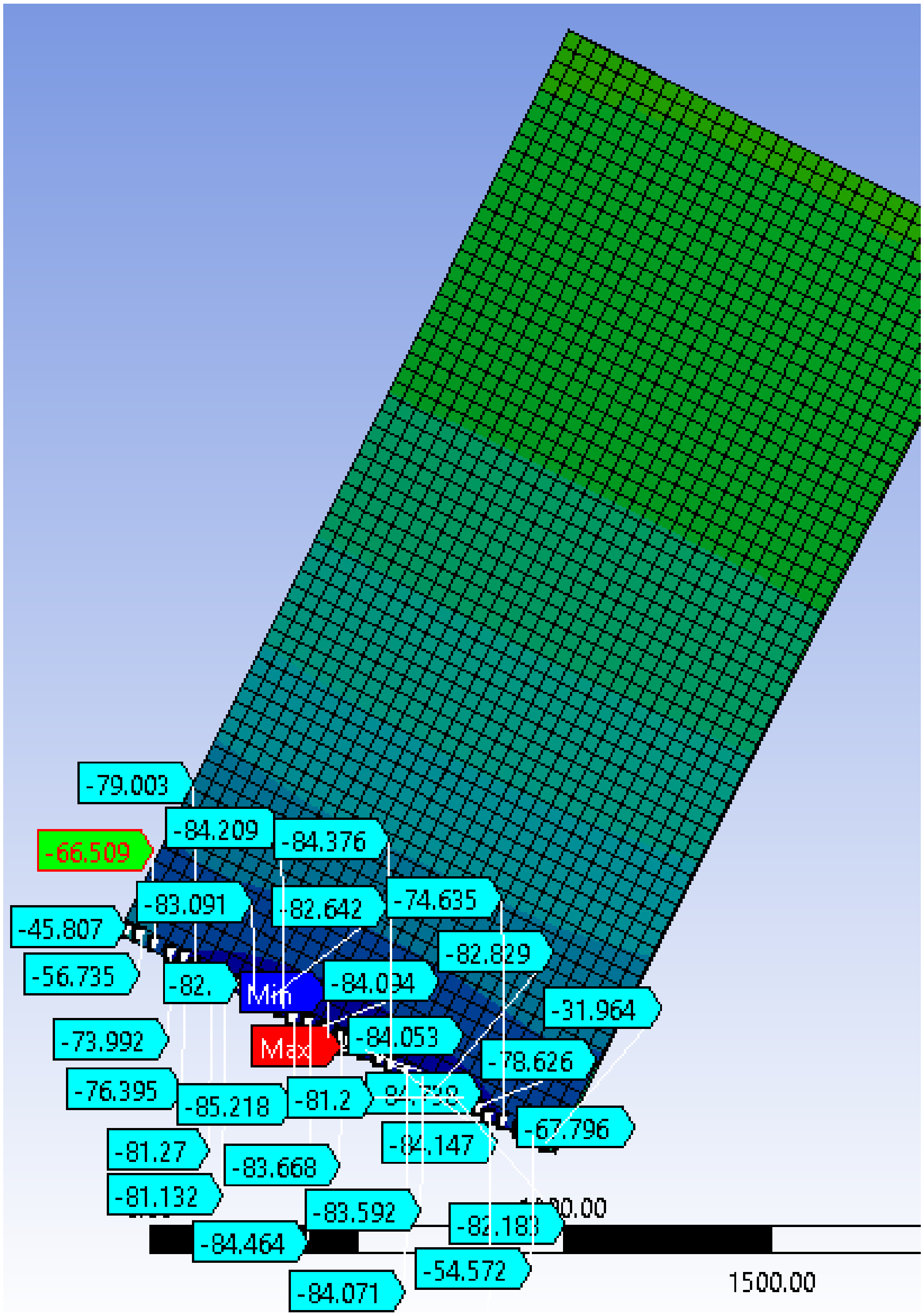
$\sigma_b := M\cdot\dfrac{c}{I} = 77.177\cdot\text{MPa}$

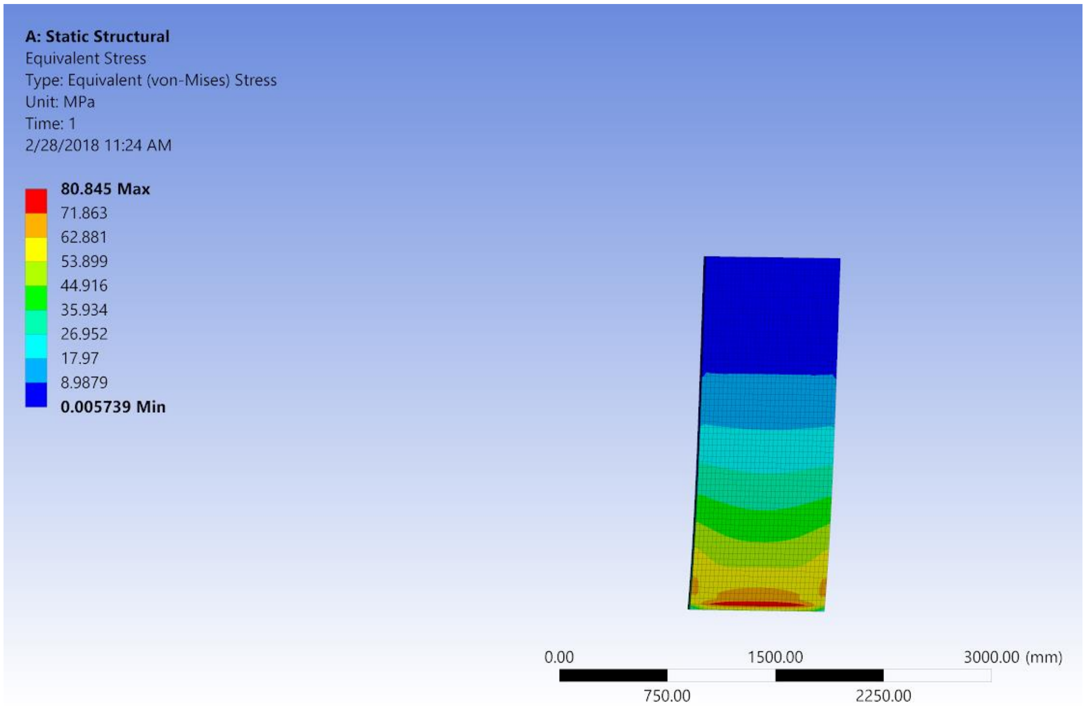
$\sigma_w + \sigma_b = 77.365\cdot\text{MPa}$

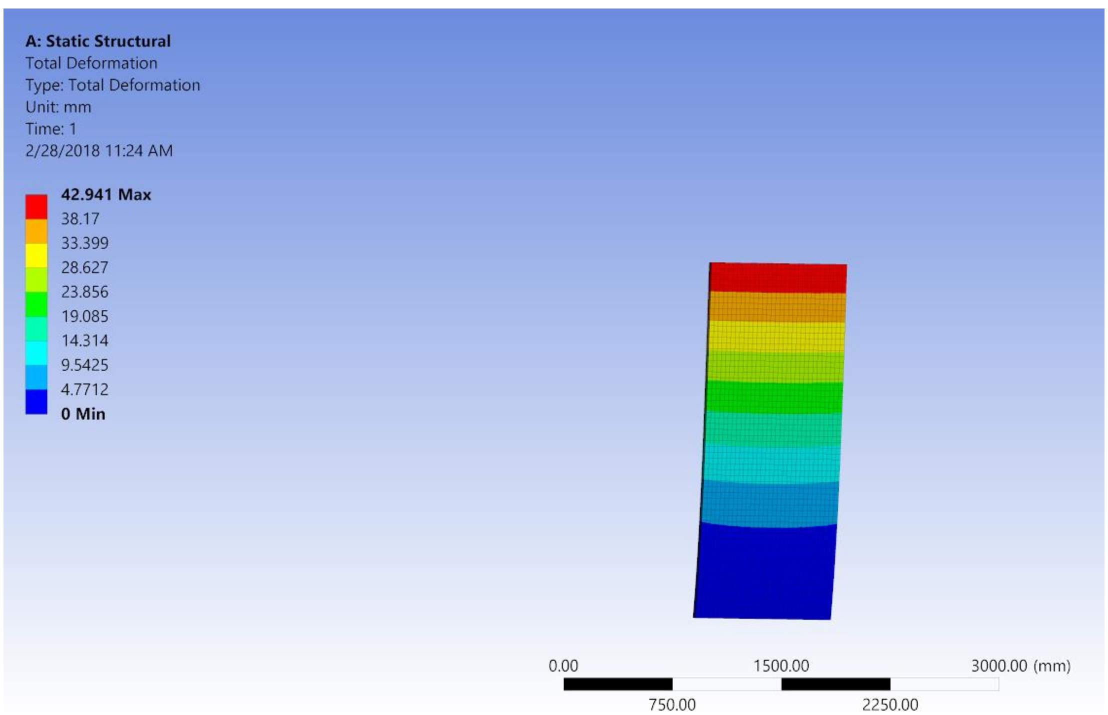
Only Axial Loading			Compressive Stress (Mpa)		
		average	-0.187		
-0.2832	-0.1787	-0.1787			
-0.195	-0.1787	-0.1787			
-0.1908	-0.1787	-0.1788			
-0.1846	-0.1787	-0.1789			
-0.1817	-0.1787	-0.1794			
-0.1803	-0.1787	-0.1802			
-0.1794	-0.1787	-0.1816			
-0.179	-0.1787	-0.1843			
-0.1788	-0.1787	-0.1891			
-0.1787	-0.1787	-0.1948			
		-0.2537			

Compressive Stress			Compressive Stress (Mpa)		
		average	-77.853		
-45.807	-82.642	-84.071			
-56.735	-84.209	-83.592			
-66.509	-85.218	-82.829			
-73.992	-84.464	-82.183			
-76.395	-84.094	-81.2			
-79.003	-83.668	-78.626			
-81.27	-84.053	-78.543			
-81.132	-84.738	-74.635			
-82	-84.147	-67.796			
-83.091	-84.376	-54.572			




-79.003
-84.209
-84.376
-66.509
-83.091
-82.642
-74.635
-45.807
-82.829
-56.735
-82.
Min
-84.034
-31.964
-73.992
Max
-84.053
-78.626
-76.395
-85.218
-81.2
-67.796
-84.147
-81.27
-83.668
-81.132
-83.592
-82.183
-84.464
-54.572
1500.00
-84.071

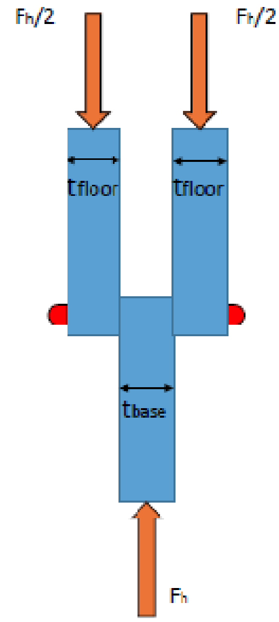

A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
2/28/2018 11:24 AM
80.845 Max
71.863
62.881
53.899
44.916
35.934
26.952
17.97
8.9879
0.005739 Min
0.00
1500.00
3000.00 (mm)
750.00
2250.00


A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
2/28/2018 11:24 AM
42.941 Max
38.17
33.399
28.627
23.856
19.085
14.314
9.5425
4.7712
0 Min
0.00
1500.00
3000.00 (mm)
750.00
2250.00

Appendix G: Hand Calculations: Hinges

Pin needed for the folding mechanism

The pins in the hinge must be able to withstand the shear forces that would be applied to it. The maximum force it would see would be applied when the floor is folded up and the weight is acting verticle on the hinge.



Weight of floor

$F_w := 1000lbf$

Weight of Floor/ #of hinges

$F_h := \frac{F_w}{2} = 500\,lbf$

The dimensions and material of the pin are as follows

Pin diameter	Leaf Length	Joint Length (floor side)	Joint Length (base side)
$D_p := \left(\frac{3}{8}\right)in$	$h := 4in$	$t_{floor} := \frac{h}{3} = 1.333\,in$	$t_{base} := t_{floor}$

Material

Steel

Yield Strength of the Material

$y_{sh} := 400MPa = 58.015\cdot ksi$

The Shear and Bearing Stress can be calculated as shown for double shear. Using these values, a Safety Factor was determined using the yeild strenght of the material.

Shear Stress

$$\tau := \frac{F_h}{2\cdot\left(\frac{\pi}{4}\cdot D_p^{\,2}\right)} = 2.264\times 10^3\,psi$$

Bearing Stress

$$\sigma_{floorbear} := \frac{\frac{F_h}{2}}{\left(t_{floor}\cdot D_p\right)} = 500\,psi$$

$$\sigma_{basebear} := \frac{F_h}{t_{base}\cdot D_p} = 1\times 10^3\,psi$$

$$\boxed{SF := \frac{y_{sh}}{\tau} = 25.63}$$

Appendix H: Fatigue Analysis Excel Spreadsheet

Page 1: Input Stress Values and Calculate Von-Mises Stresses for mean and alternating portions.

	Mean Stresses		Alternating Stresses	Input Units	Von-Mises Stresses		
	Normal			Mpa	Mean	4.576024	Mpa
x	-3	x	1.90E+01		Alternating	49.55805	Mpa
y	0	y	0				
z	0	z	0				
	Shear						
x	-0.7	x	17				
y	0	y	0				
z	0	x	0				

Page 2: Select or input environmental factors to find material correction factors.

Select Load Type		
Bending		
Select Size Parameters		
Rectangular Cross Sections		
in		
Enter Diameter		
6		
Enter A95	**Equivalent Diameter**	
184	49.01110867	
Surface Type		
0.85		
Enter Temperature		
Farenheit		
100		
Select Desired Reliability		
99.9%		

	Fatigue Limit
Standard Value	225
Load Correction	1
Size Correction	0.6
Surface Correction	0.85
Temperature Correction	1
Reliability Correction	0.753
Corrected Value	86.40675

Typical Non-Cylindrical Cross Sections	
Rectangle	
Height	80
Width	46

Page 2 continued: Including notes on correction factors necessary for creating drop-down menus.

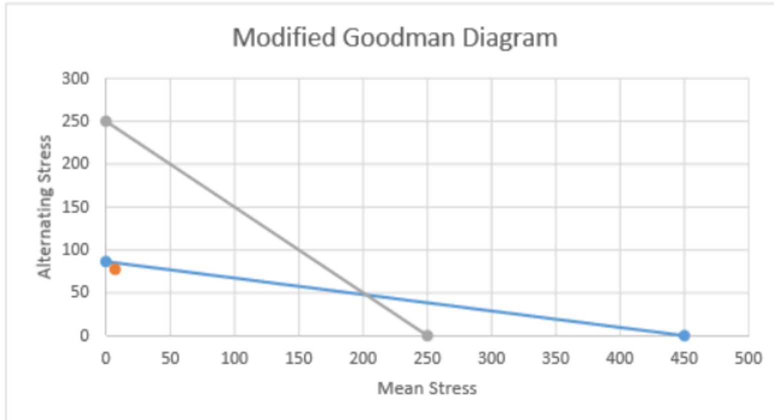
Ultimate Strength		Notes:		
450	Mpa	Load Correction	Bending	C = 1
1			Axial Loading	C = 0.70
0.6			Pure Torsion	C = 1
0.85		Size Correction	d <= 0.3 in (8mm)	C = 1
1		in	0.3 in < d <= 10 in	C = 0.869d^(-0.097)
0.753		mm	8mm < d <= 250 mm	C = 1.189d^(-0.097)
172.8135	Mpa	Surface Correction		
A95		Temperature Correction	T <= 450 C (840 F)	C = 1
		Celsius	450 C < T <= 550 C	C = 1 - 0.0058 (T-450)
		Farenheit	840 F < T <= 1020 F	C = 1 - 0.0032 (T-840)
184		Reliability Correction	50%	C = 1
			90%	C = 0.897
			95%	C = 0.868
			99%	C = 0.814
			99.9%	C = 0.753
			99.99%	C = 0.702
			99.999%	C = 0.659
			99.9999%	C = 0.620
		Cylindrical Cross Section		
		Rectangular Cross Sections		

Page 3: Input Stress Concentration Factors.

Input fatigue Coefficient	1
Input Kt	1.7
Input Notch Sensitivity (q)	0.8

Page 4: Returns corrected stresses, safety factors for multiple cases, and Modified Goodman Diagram.

	New (pg 411)	
Midrange Stress	4.576024	Mpa
Alternating Stress	49.55805	Mpa
Kf	1.56	
Corrected Midrange	7.138598	Mpa
Corrected Alternating	77.31055	Mpa
Case 1 N Value	1.274227	
Case 2 N Value	1.07149	
Case 3 N Value	1.068335	
Case 4 N Value		



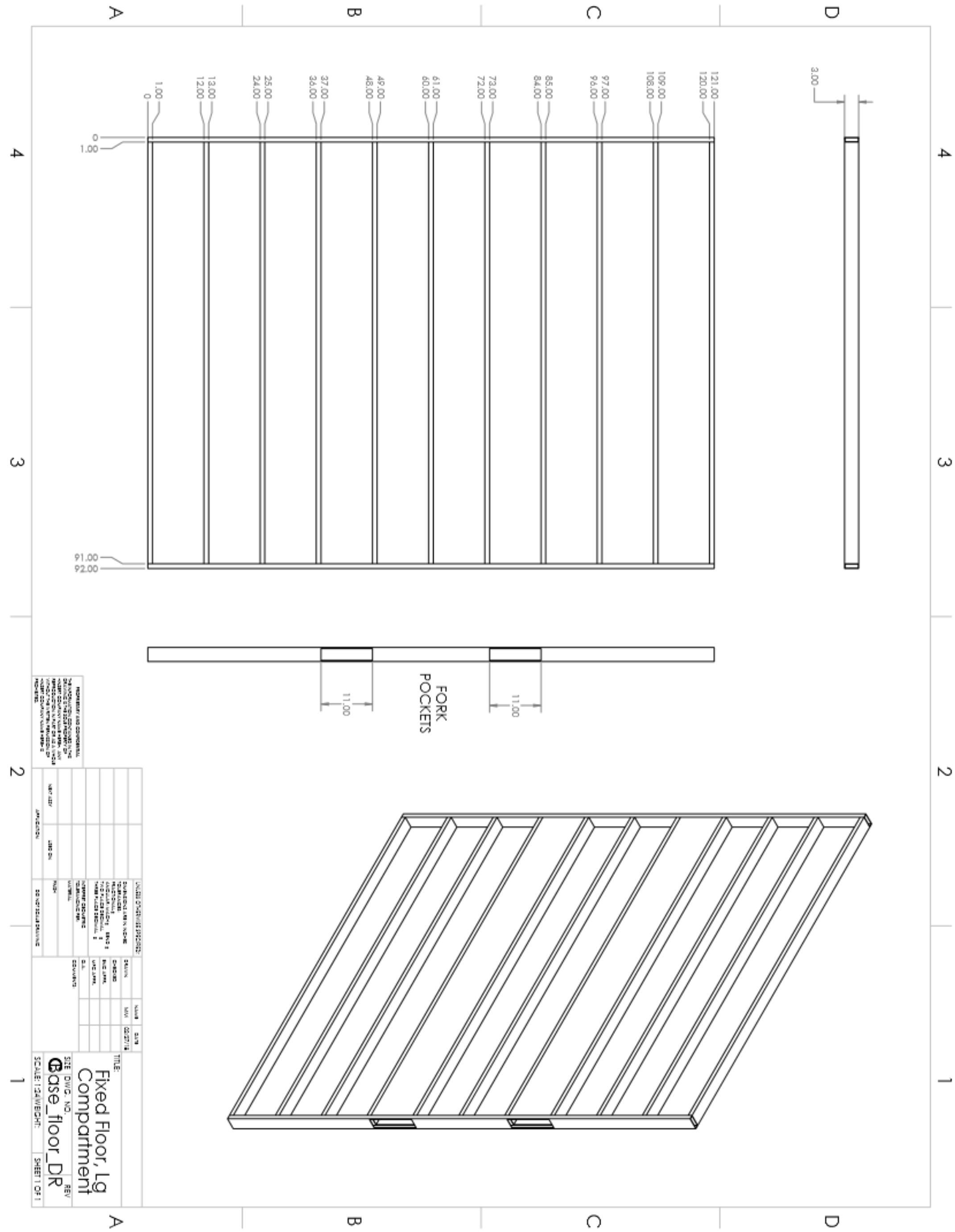
Page 4 Continued: Shows points necessary to generate graph automatically.

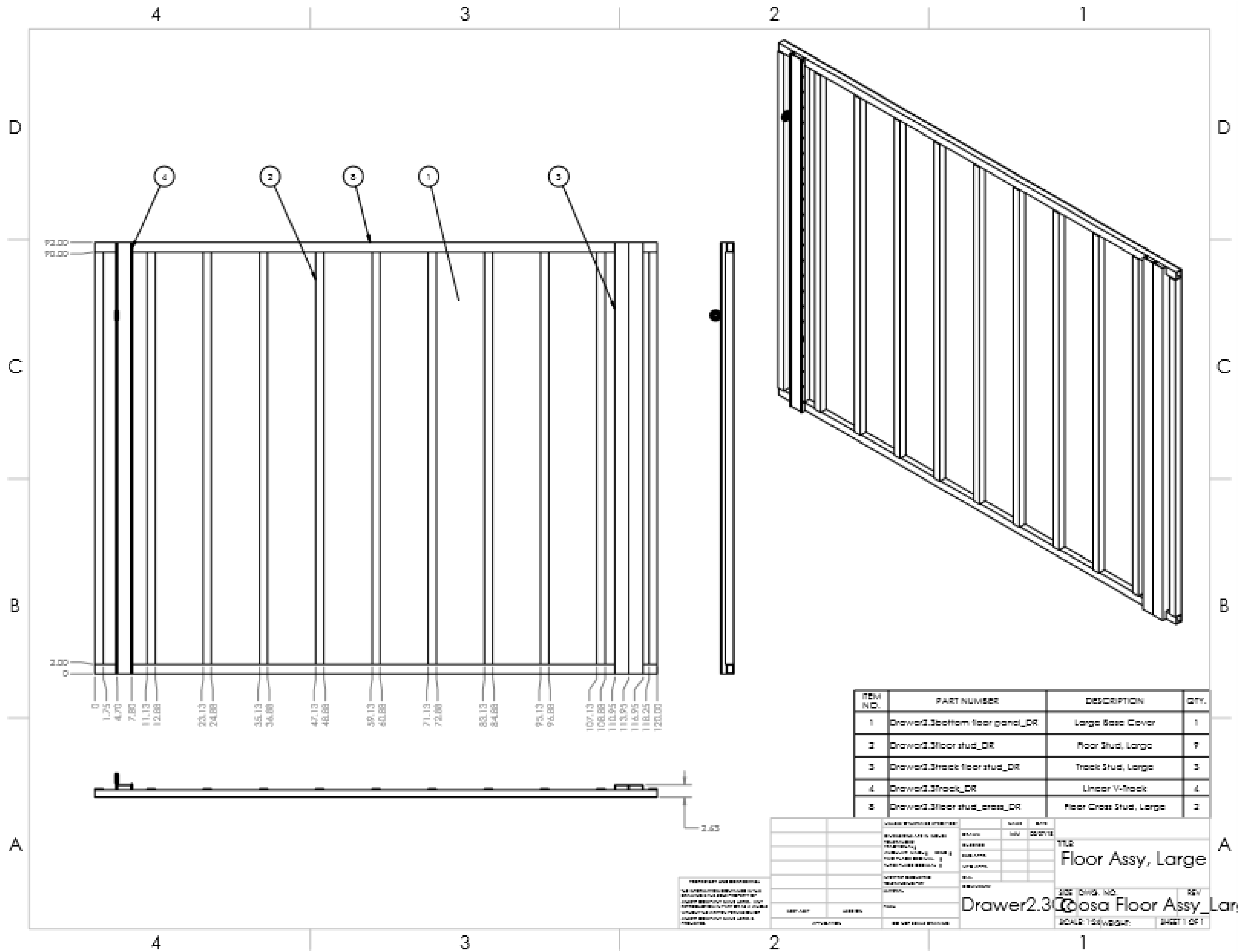
	Points	
	x	y
Stress State	7.138598182	77.31055297
Ultimate	450	0
Endurance	0	86.40675
Yield Mean	250	0
Yield Alternating	0	250

Page 5: Shows calculated values for cycles to failure formula.

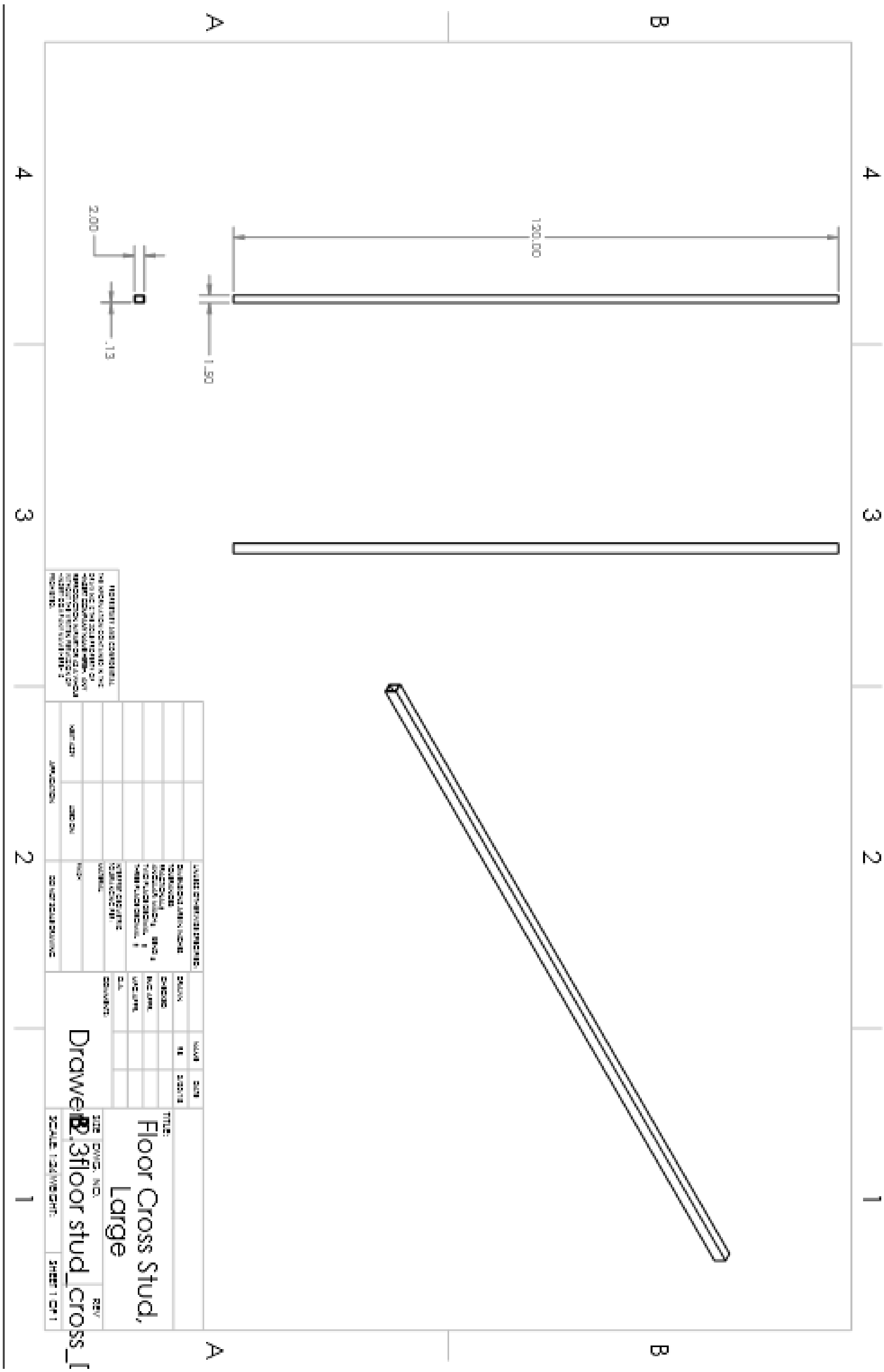
a value	345.627
b value	-0.10034333
Reversible Equivalent	80.64170915
Cycles to Failure	1990001.516

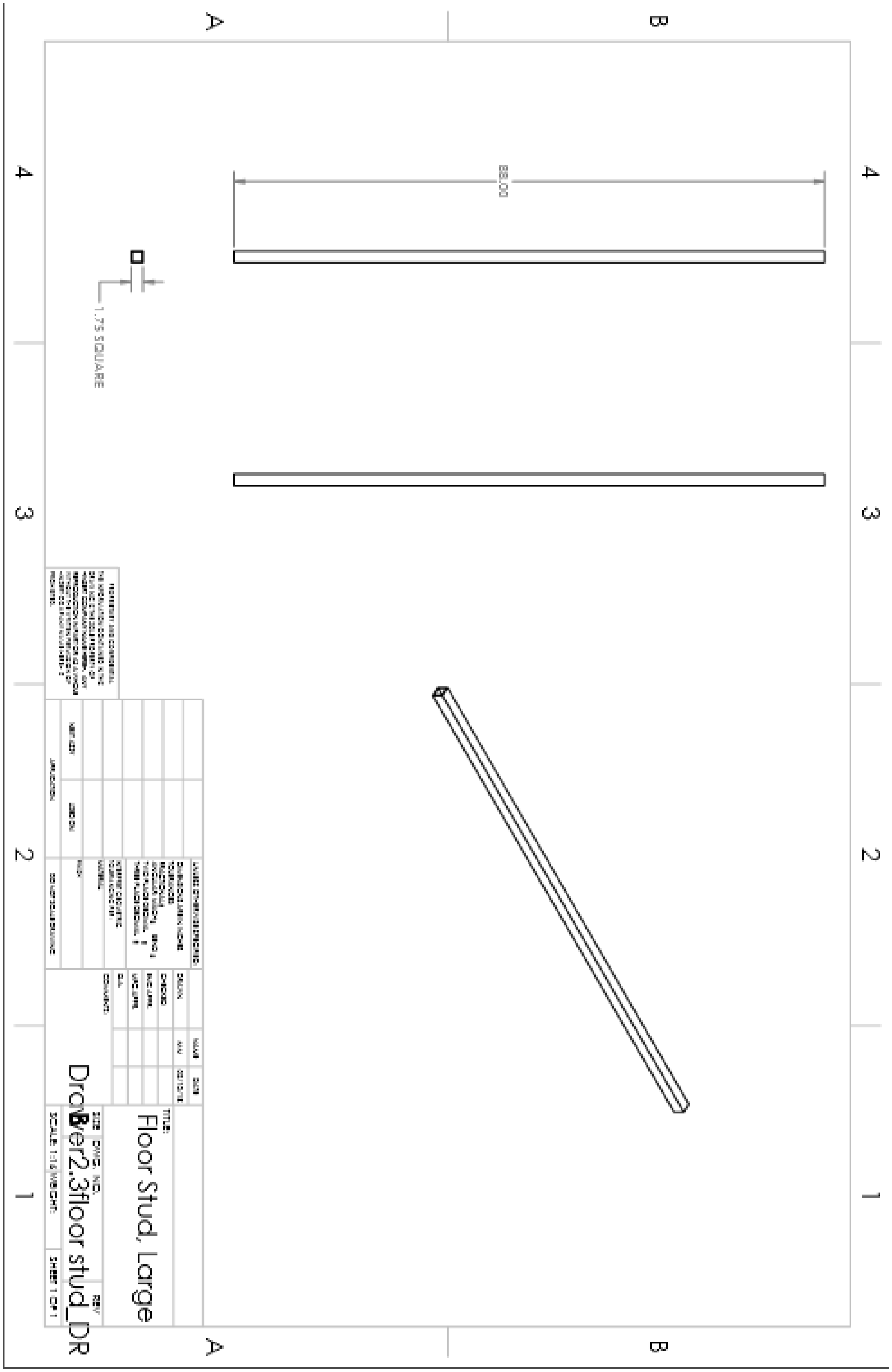
Appendix I: Detailed CAD Drawings

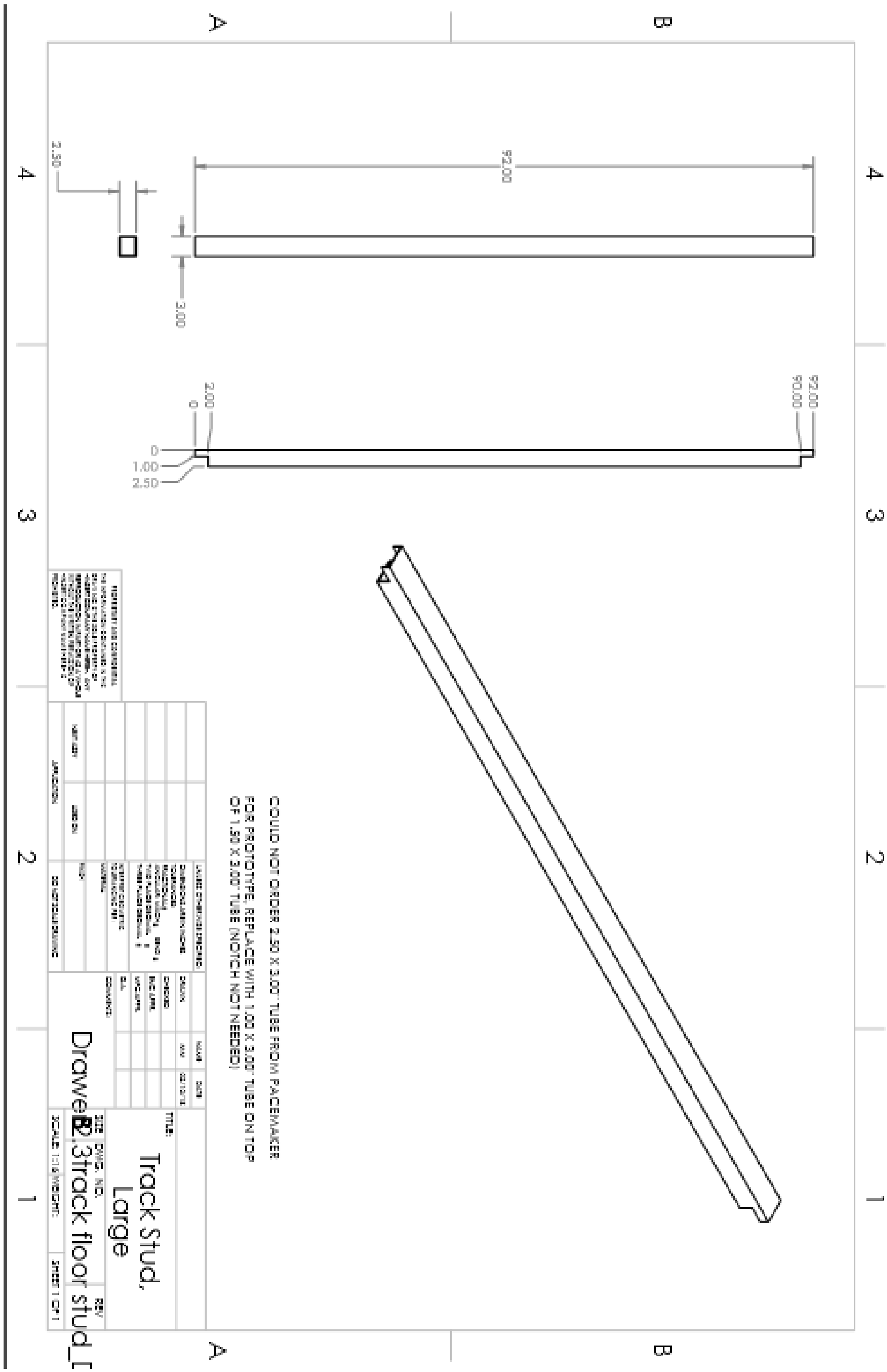




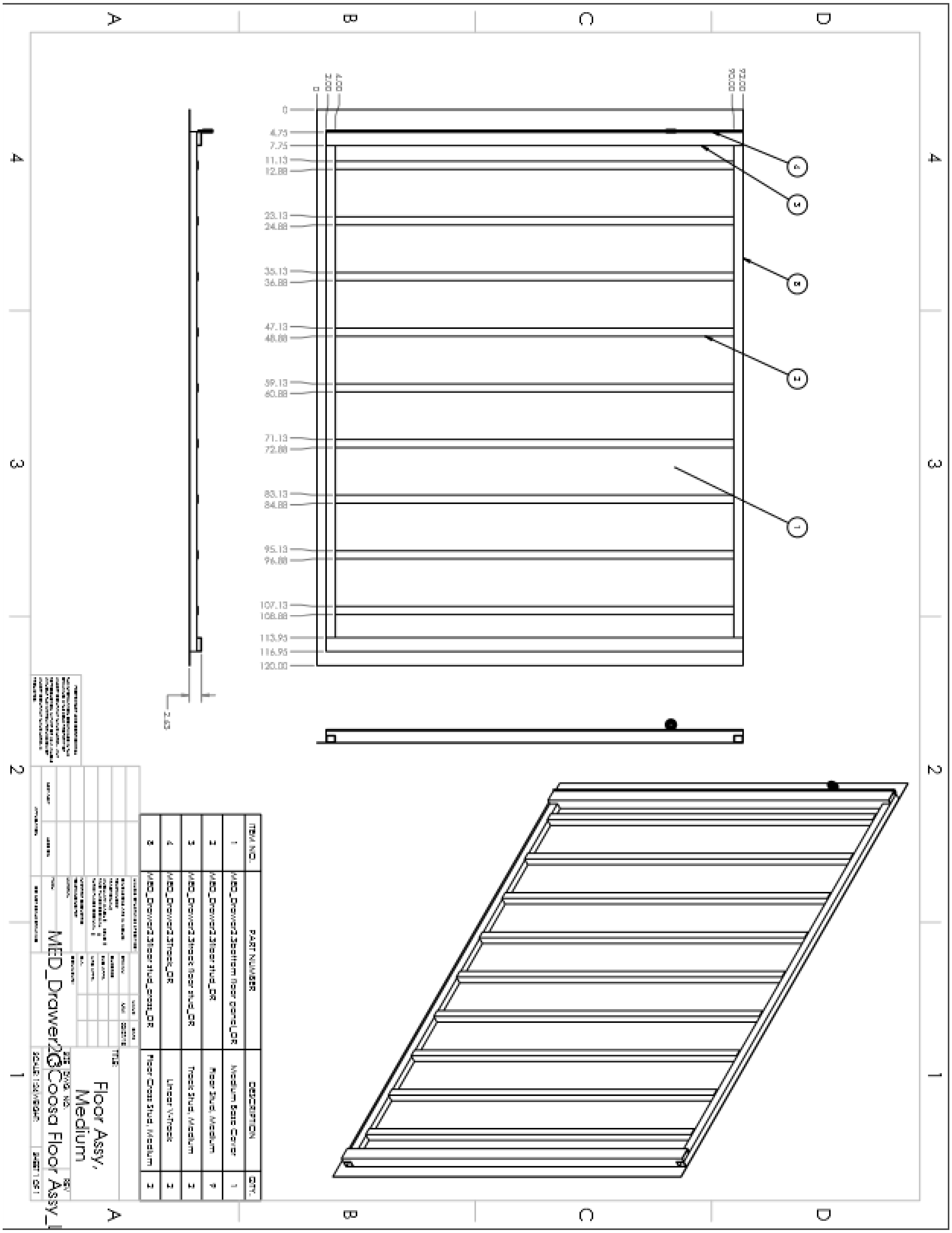
ITEM NO.
PART NUMBER
DESCRIPTION
QTY.
1 Drawer2.3bottom floor panel_DR Large Base Cover 1
2 Drawer2.3floor stud_DR Floor Stud, Large 9
3 Drawer2.3track floor stud_DR Track Stud, Large 3
4 Drawer2.3track_DR Linear V-Track 4
5 Drawer2.3floor stud_cross_DR Floor Cross Stud, Large 2
TITLE:
Floor Assy, Large
Drawer2.3Coosa Floor Assy_Lar


120.00
1.50
2.00
.13
TITLE:
Floor Cross Stud, Large
SIZE
DWG. NO.
REV
SCALE: 1:24 WEIGHT:
SHEET 1 OF 1

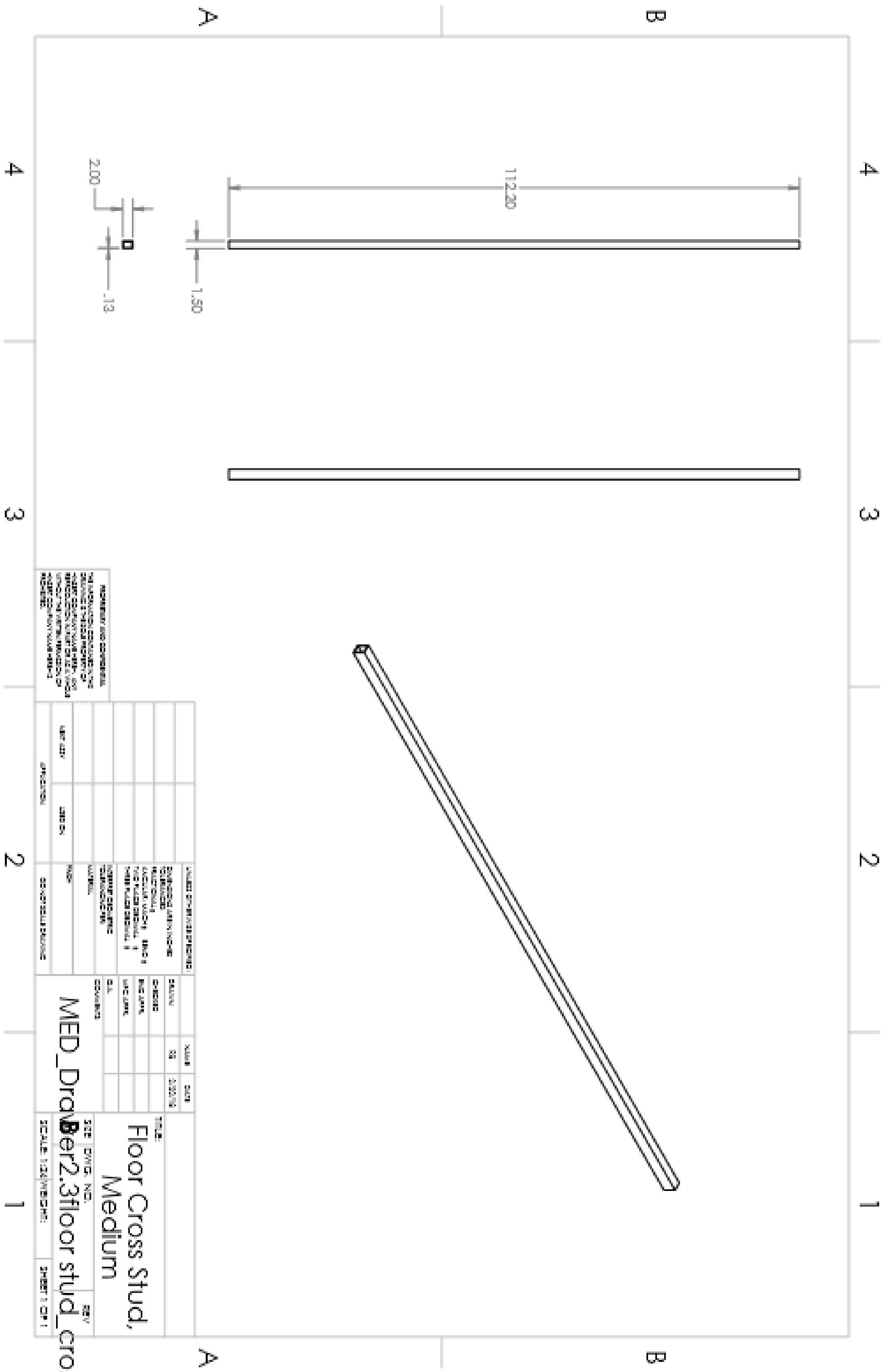

88.00
1.75 SQUARE
TITLE:
Floor Stud, Large
SIZE B DWG. NO.
Drawer2.3floor stud_DR
REV
SCALE: 1:16 WEIGHT:
SHEET 1 OF 1



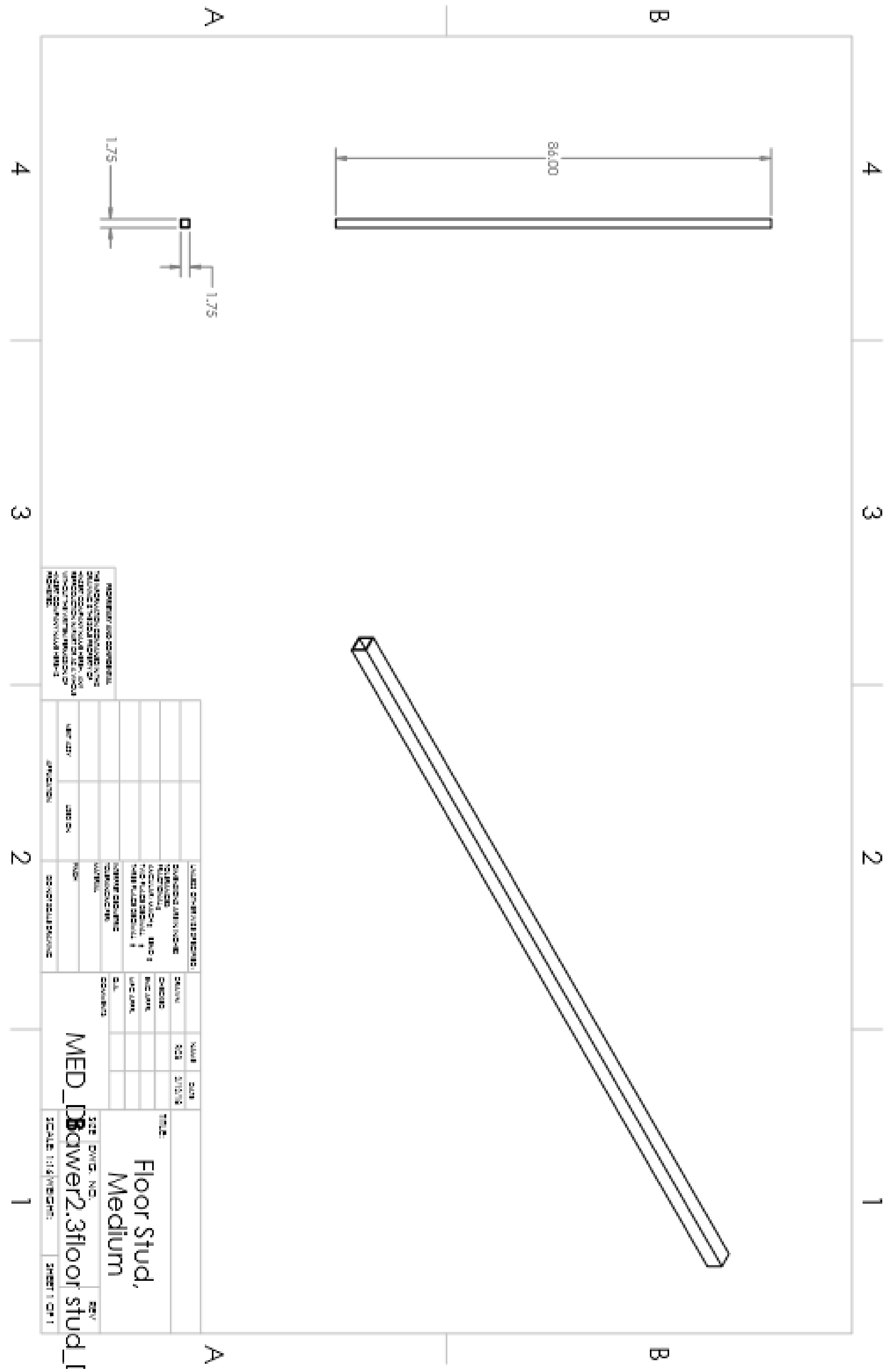
92.00
3.00
2.50
90.00
2.00
0
1.00
COULD NOT ORDER 2.50 X 3.00" TUBE FROM PACEMAKER
FOR PROTOTYPE, REPLACE WITH 1.00 X 3.00" TUBE ON TOP OF 1.50 X 3.00" TUBE (NOTCH NOT NEEDED)
TITLE:
Track Stud, Large
SIZE DWG. NO. REV
B
SCALE: 1:16 WEIGHT: SHEET 1 OF 1

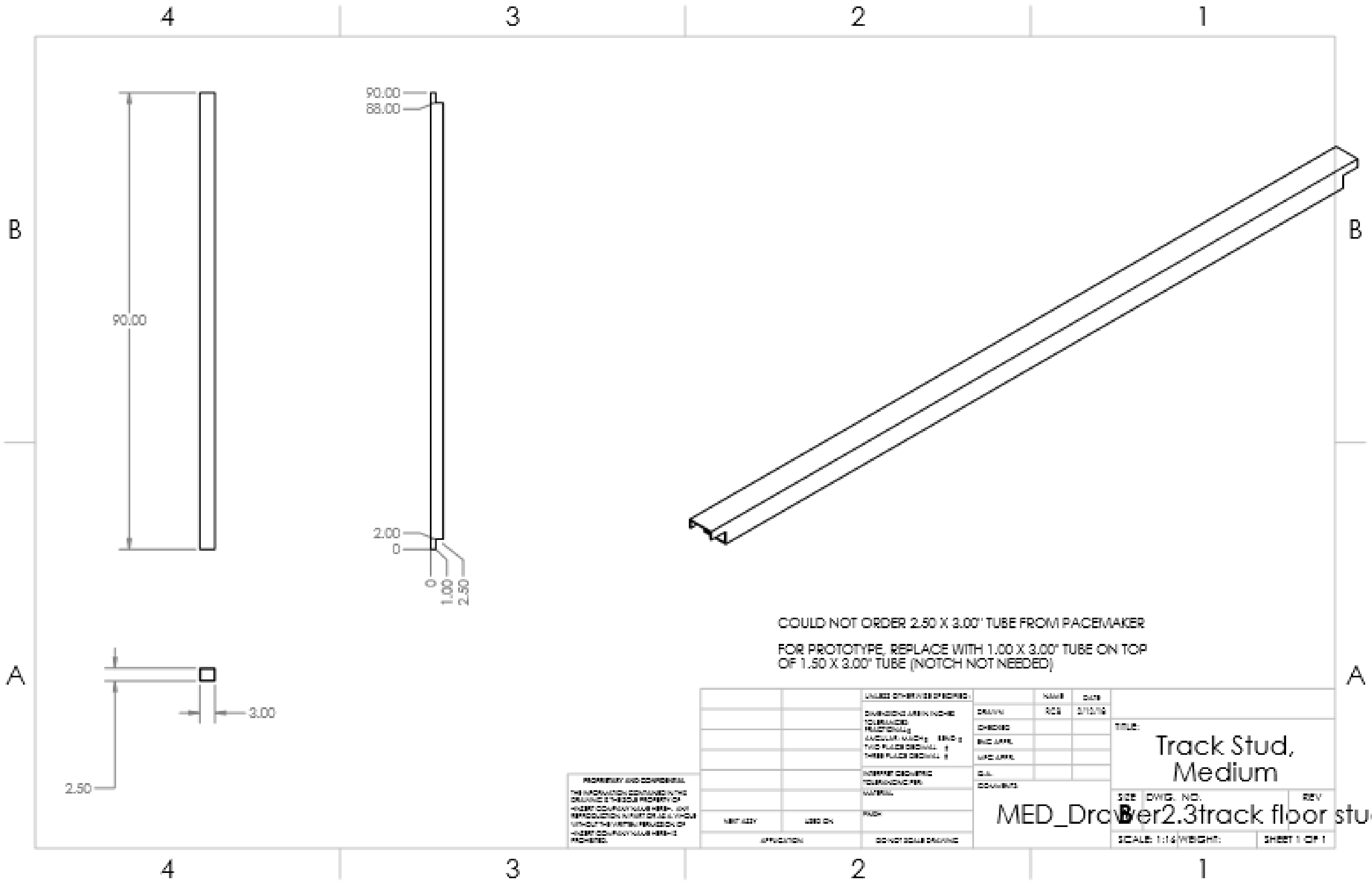


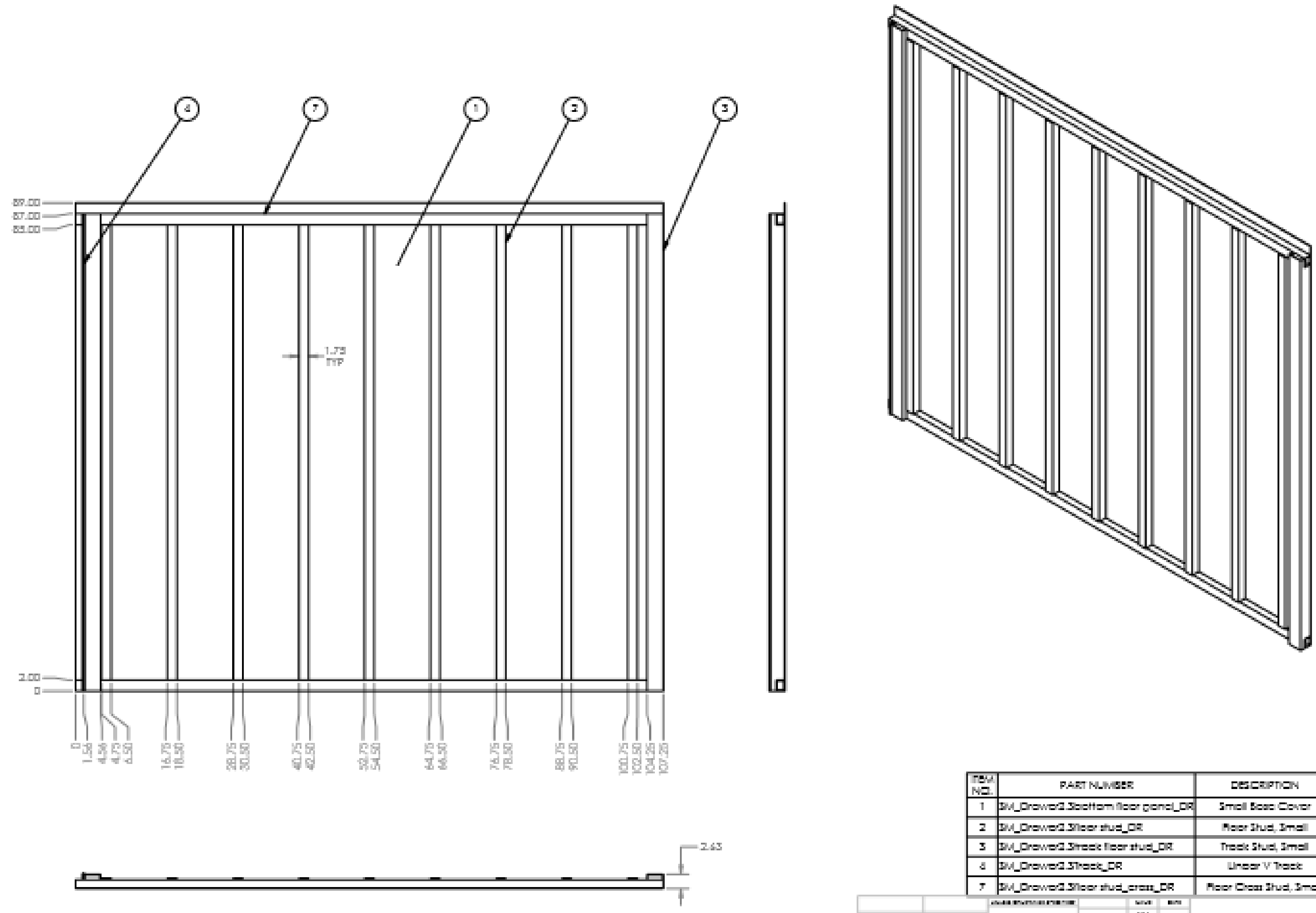
ITEM NO. | PART NUMBER | DESCRIPTION | QTY.
1 | MED_Drawer2 Medium floor panel_DR | Medium Base Cover | 1
2 | MED_Drawer2 Floor stud_DR | Floor Stud, Medium | 9
3 | MED_Drawer2 Track floor stud_DR | Track Stud, Medium | 2
4 | MED_Drawer2 Track_DR | Linear V-Track | 2
5 | MED_Drawer2 Floor stud_cross_DR | Floor Cross Stud, Medium | 2
TITLE:
Floor Assy, Medium
SIZE
DWG. NO.
MED_Drawer2GCoosa Floor Assy_
REV
SCALE: 1:24
SHEET 1 OF 1
0
4.75
7.75
11.13
12.88
23.13
24.88
35.13
36.88
47.13
48.88
59.13
60.88
71.13
72.88
83.13
84.88
95.13
96.88
107.13
108.88
113.95
116.95
120.00
0
2.00
4.00
90.00
93.00
2.63



112.20
1.50
2.00
.13
TITLE:
Floor Cross Stud,
Medium
MED_Drawer2.3floor stud_cro
SIZE
B
DWG. NO.
REV
SCALE: 1:24
WEIGHT:
SHEET 1 OF 1
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL


86.00
1.75
1.75
Floor Stud,
Medium
MED_Drawer2.3floor stud_[


90.00
90.00
88.00
2.00
0
0
1.00
2.50
3.00
2.50
COULD NOT ORDER 2.50 X 3.00" TUBE FROM PACEMAKER
FOR PROTOTYPE, REPLACE WITH 1.00 X 3.00" TUBE ON TOP
OF 1.50 X 3.00" TUBE (NOTCH NOT NEEDED)
NAME
DATE
DRAWN
RCB
TITLE:
Track Stud,
Medium
SIZE
DWG. NO.
REV
B
MED_Drawer2.3track floor stu
SCALE: 1:16
WEIGHT:
SHEET 1 OF 1

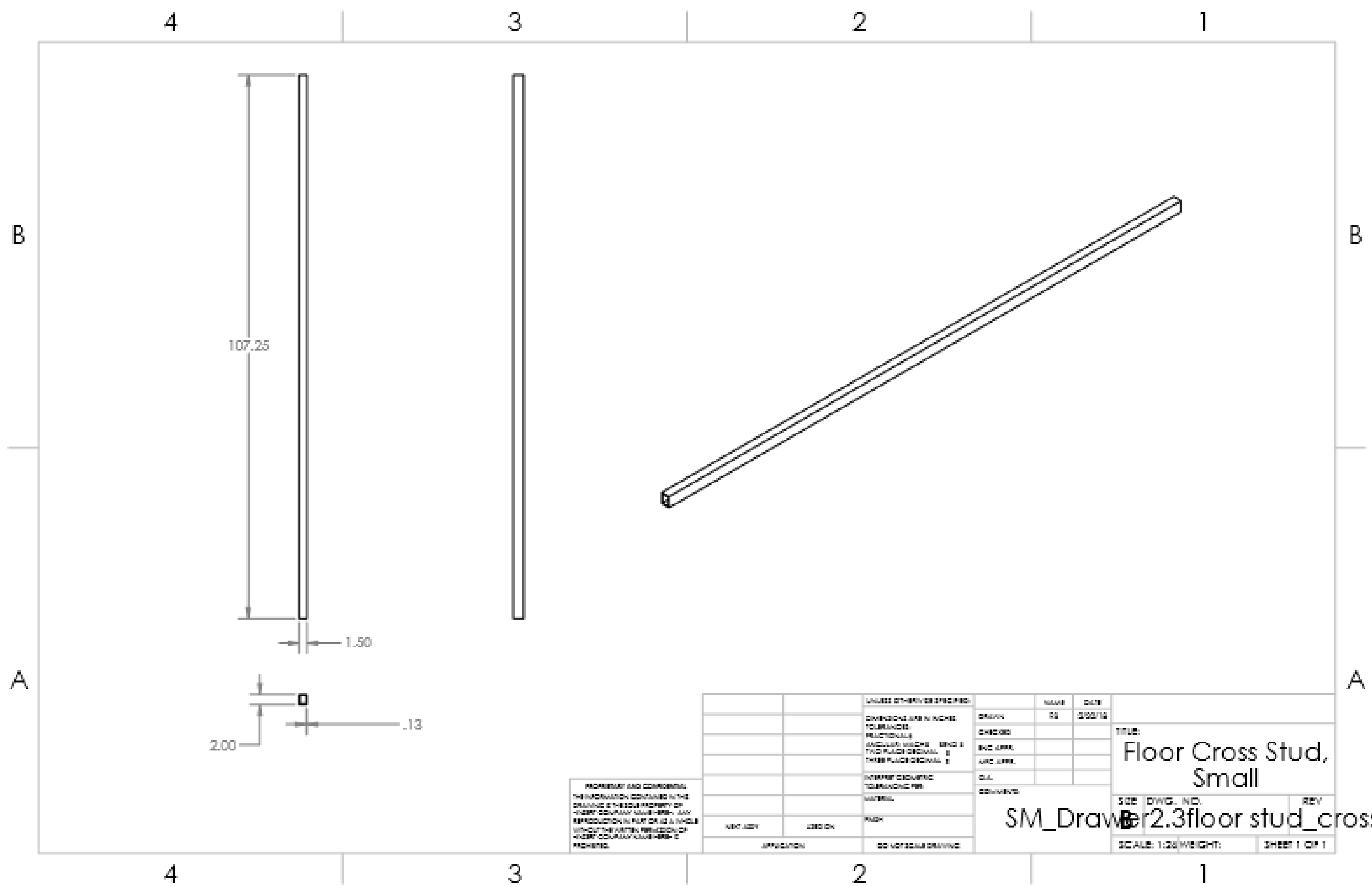


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	SM_Drawer2.3bottom floor panel_DR	Small Base Cover	1
2	SM_Drawer2.3floor stud_DR	Floor Stud, Small	9
3	SM_Drawer2.3track floor stud_DR	Track Stud, Small	2
4	SM_Drawer2.3Track_DR	Linear V Track	2
7	SM_Drawer2.3floor stud_cross_DR	Floor Cross Stud, Small	2

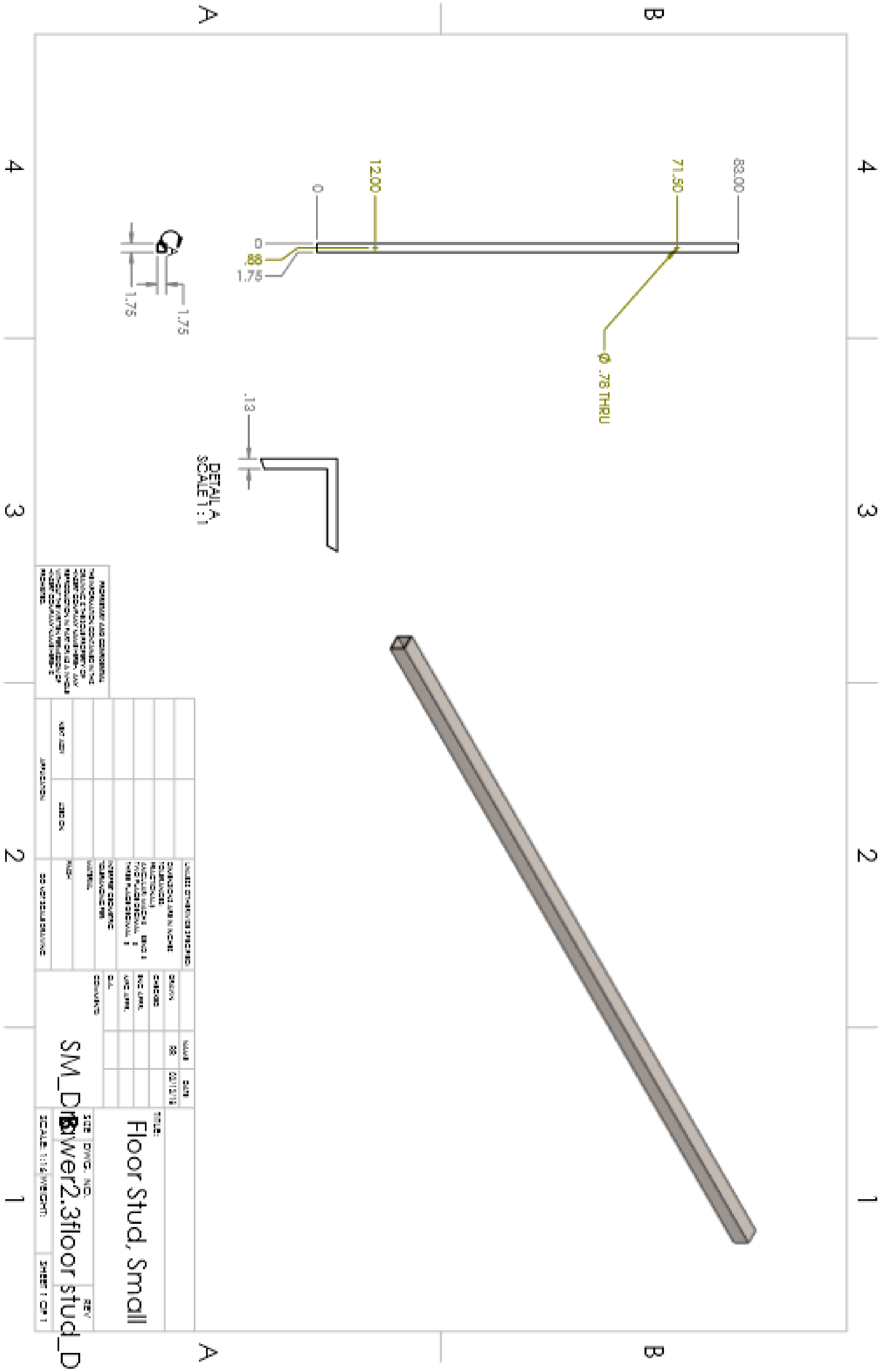
TITLE:
Floor Assy, Small

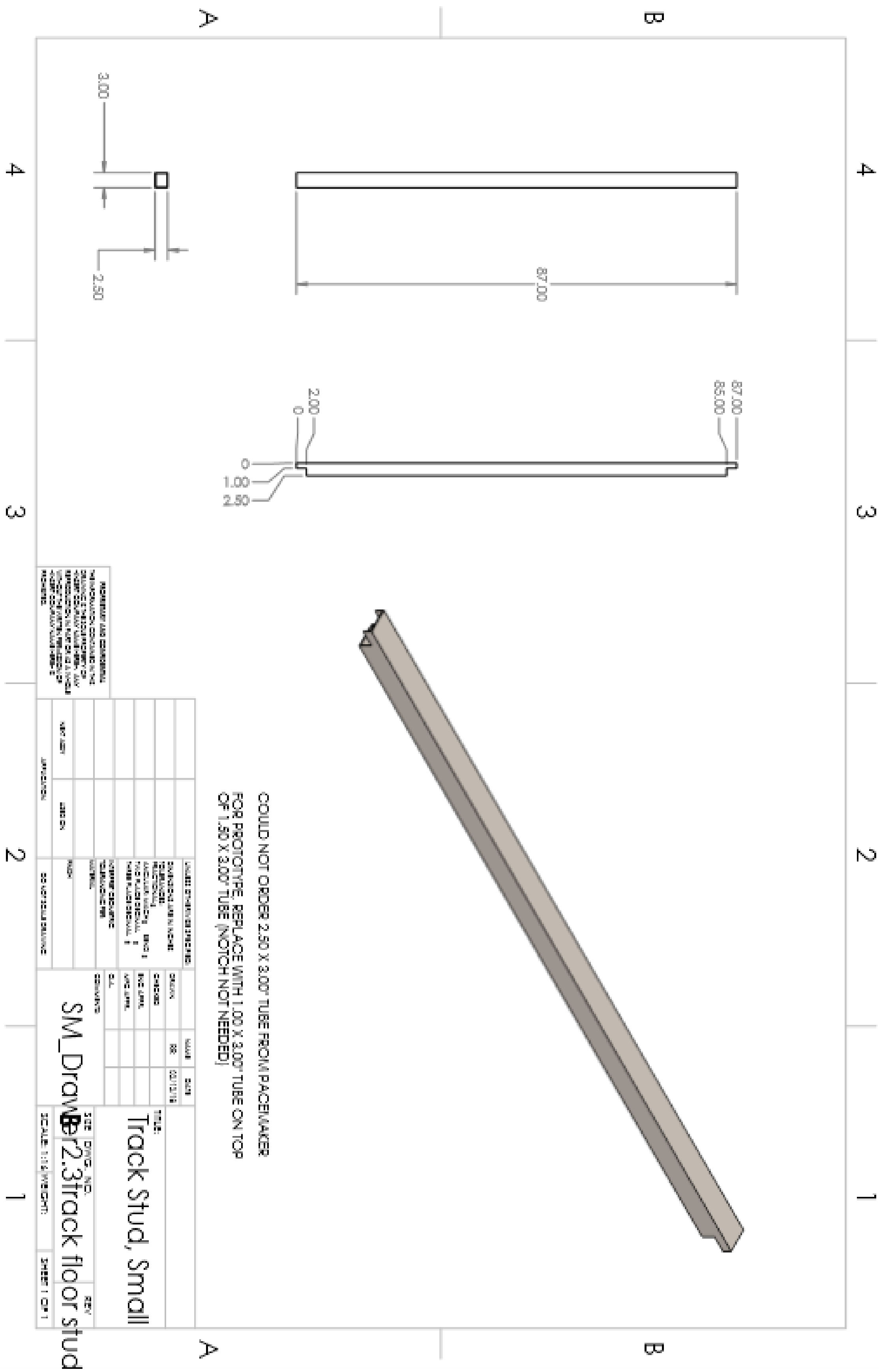
SIZE DWG. NO. REV
SM_Drawer2.3Coosa Floor Assy_L

SCALE: 1:24 WEIGHT: SHEET 1 OF 1

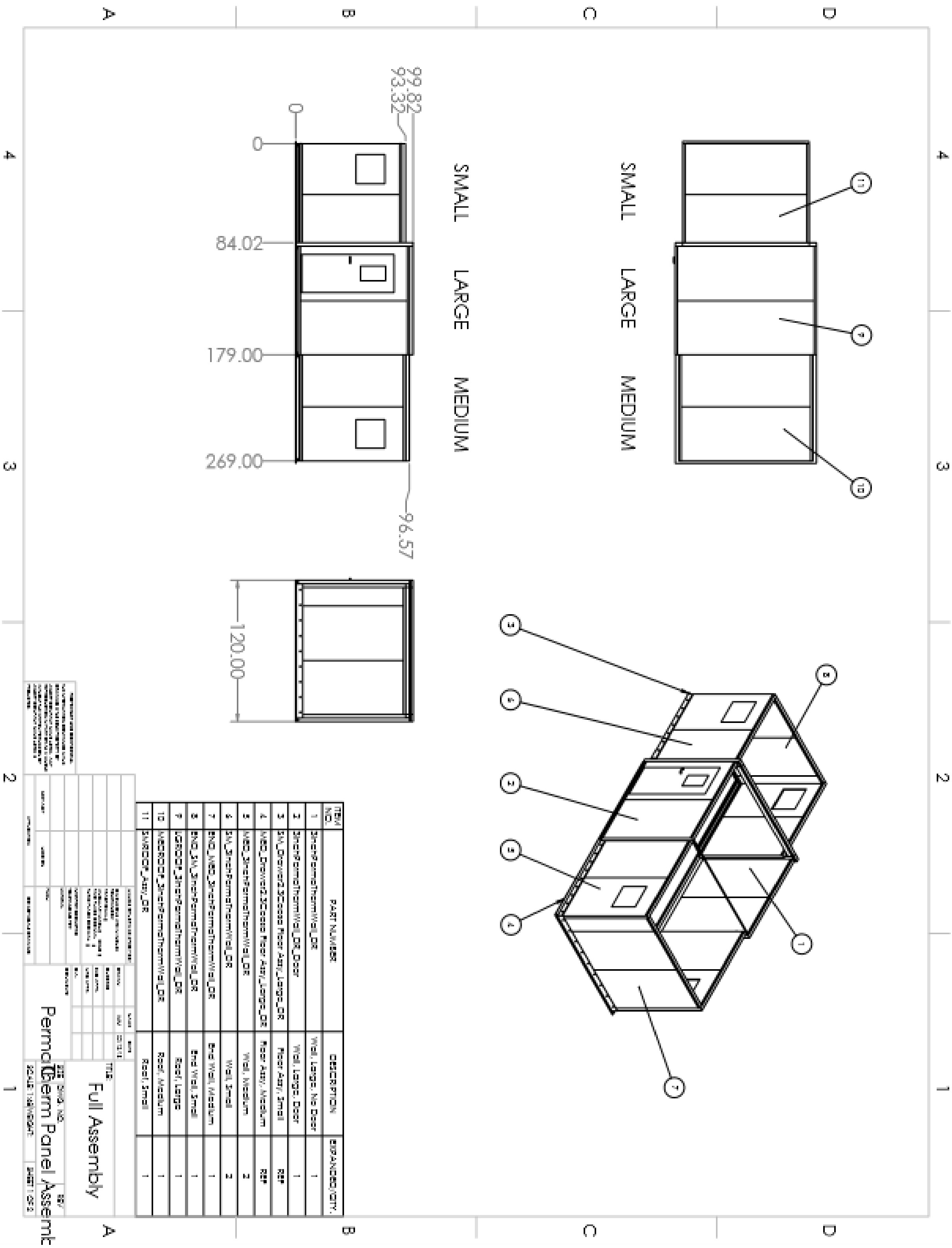


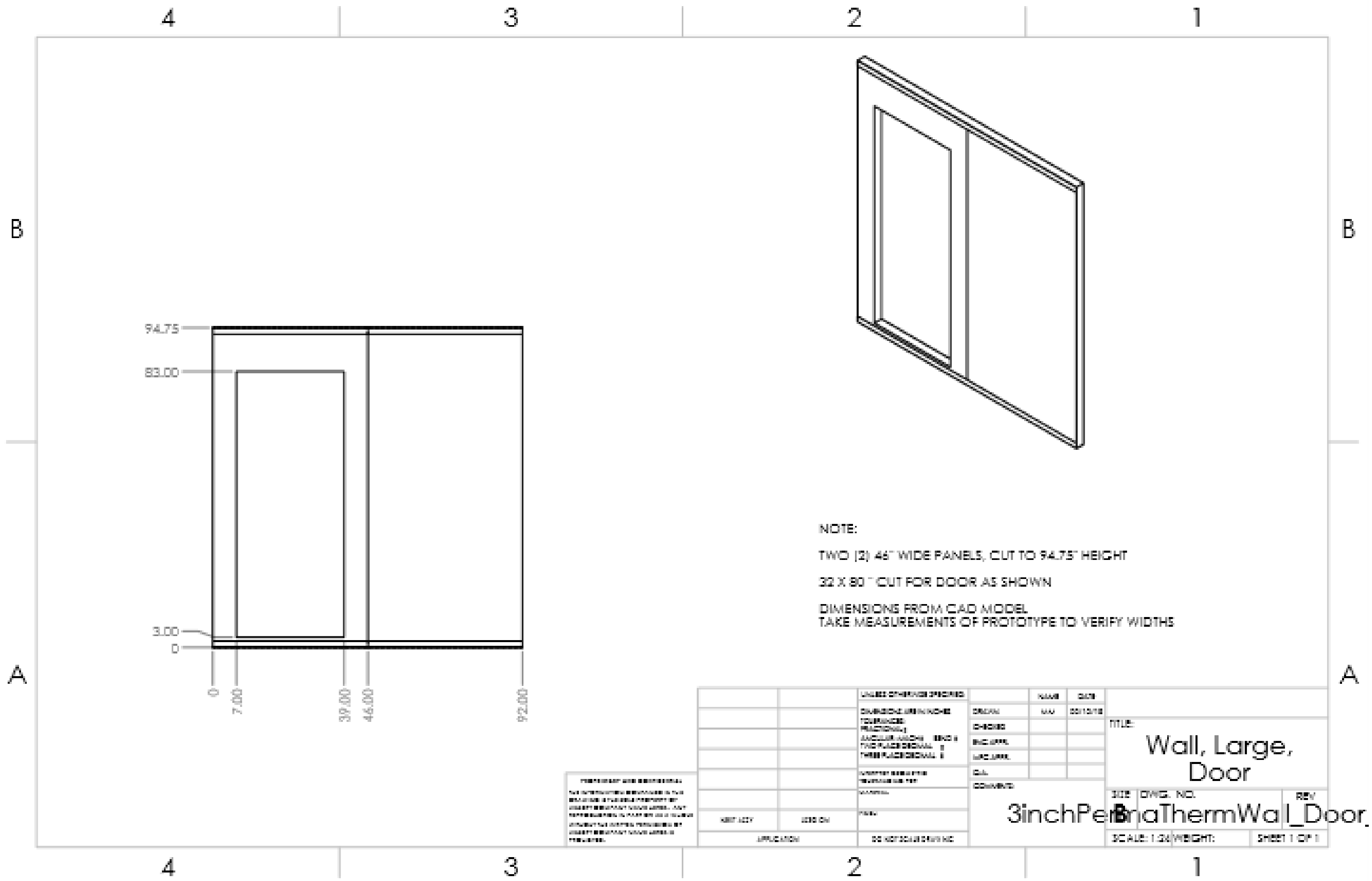
107.25
1.50
.13
2.00
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DRAWN
SS
2/20/18
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
TITLE:
Floor Cross Stud, Small
SIZE
B
DWG. NO.
SM_Drawer2.3floor stud_cros
REV
WEIGHT:
SHEET 1 OF 1


83.00
71.50
12.00
0
0
.88
1.75
1.75
1.75
Ø .75 THRU
.13
DETAIL A
SCALE 1 : 1
TITLE:
Floor Stud, Small
SIZE
DWG. NO.
REV
B
SM_Drawer2.3floor stud_D
SHEET 1 OF 1

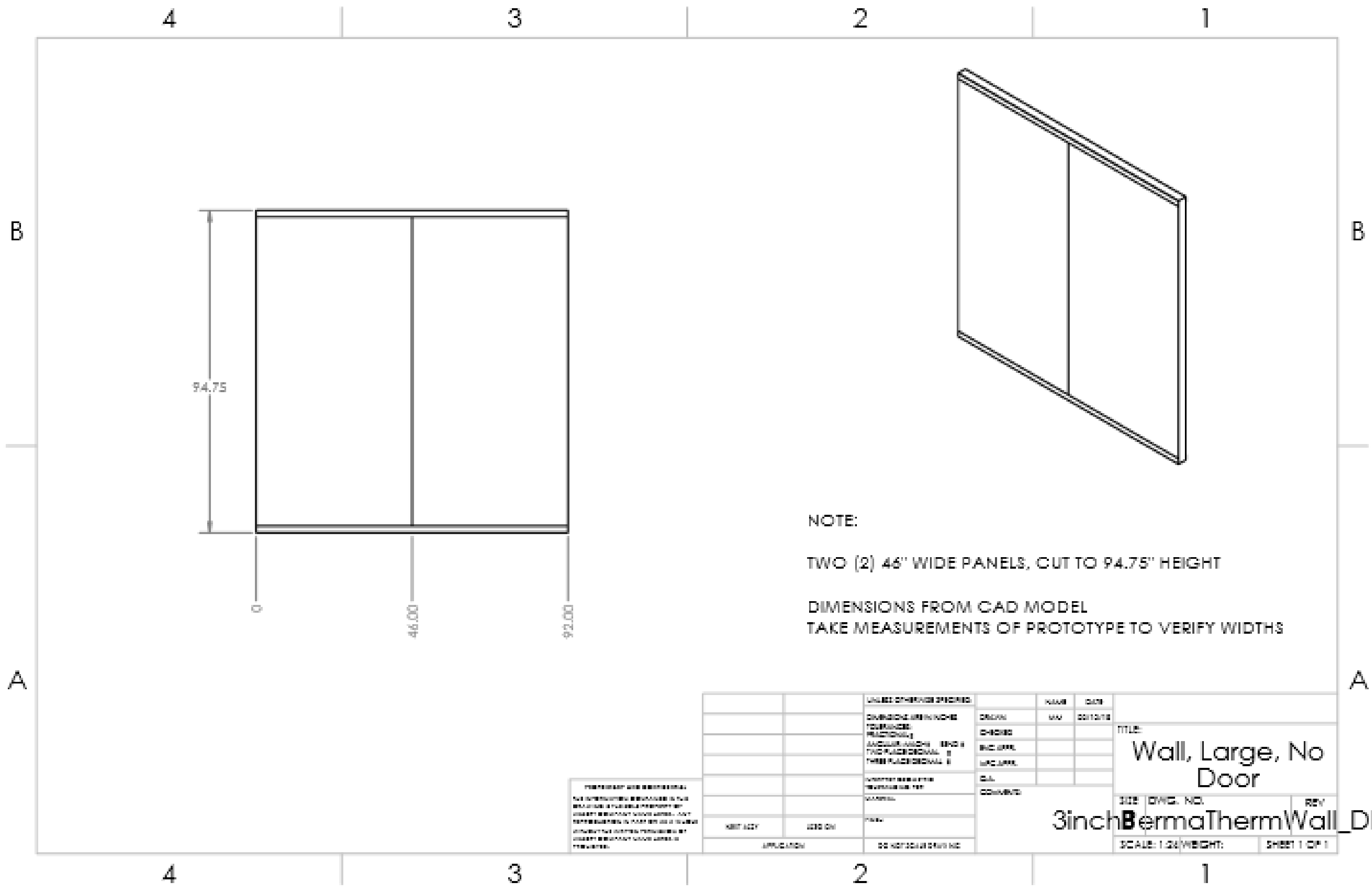


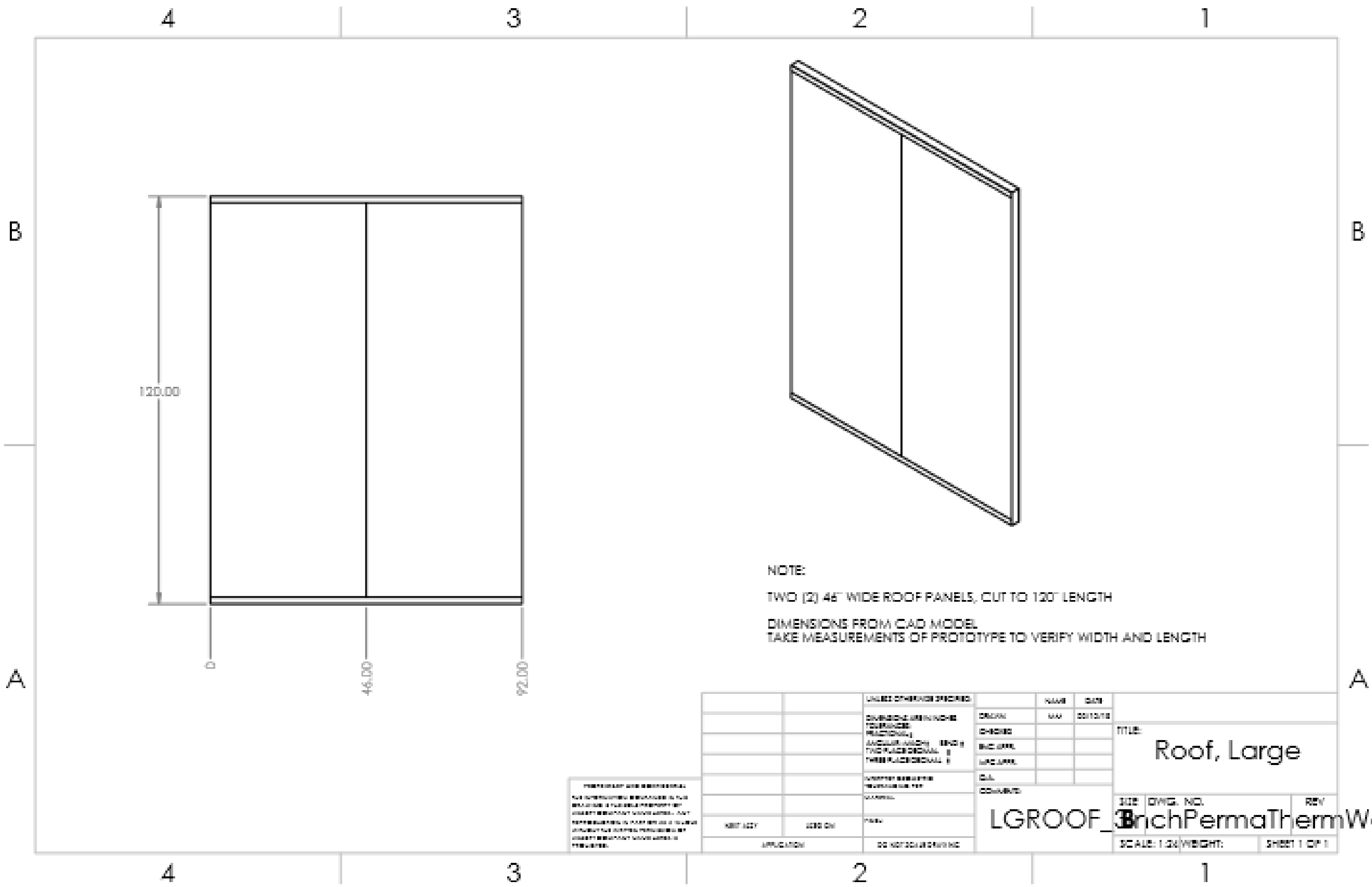
3.00
2.50
87.00
87.00
85.00
2.00
0
0
1.00
2.50
COULD NOT ORDER 2.50 X 3.00" TUBE FROM PACEMAKER
FOR PROTOTYPE, REPLACE WITH 1.00 X 3.00" TUBE ON TOP
OF 1.50 X 3.00" TUBE (NOTCH NOT NEEDED)
NAME
DATE
DRAWN
02/12/18
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Track Stud, Small
SIZE
B
DWG. NO.
REV
SM_Drawer2.3track floor stud
SCALE: 1:16
WEIGHT:
SHEET 1 OF 1
A
B
1
2
3
4

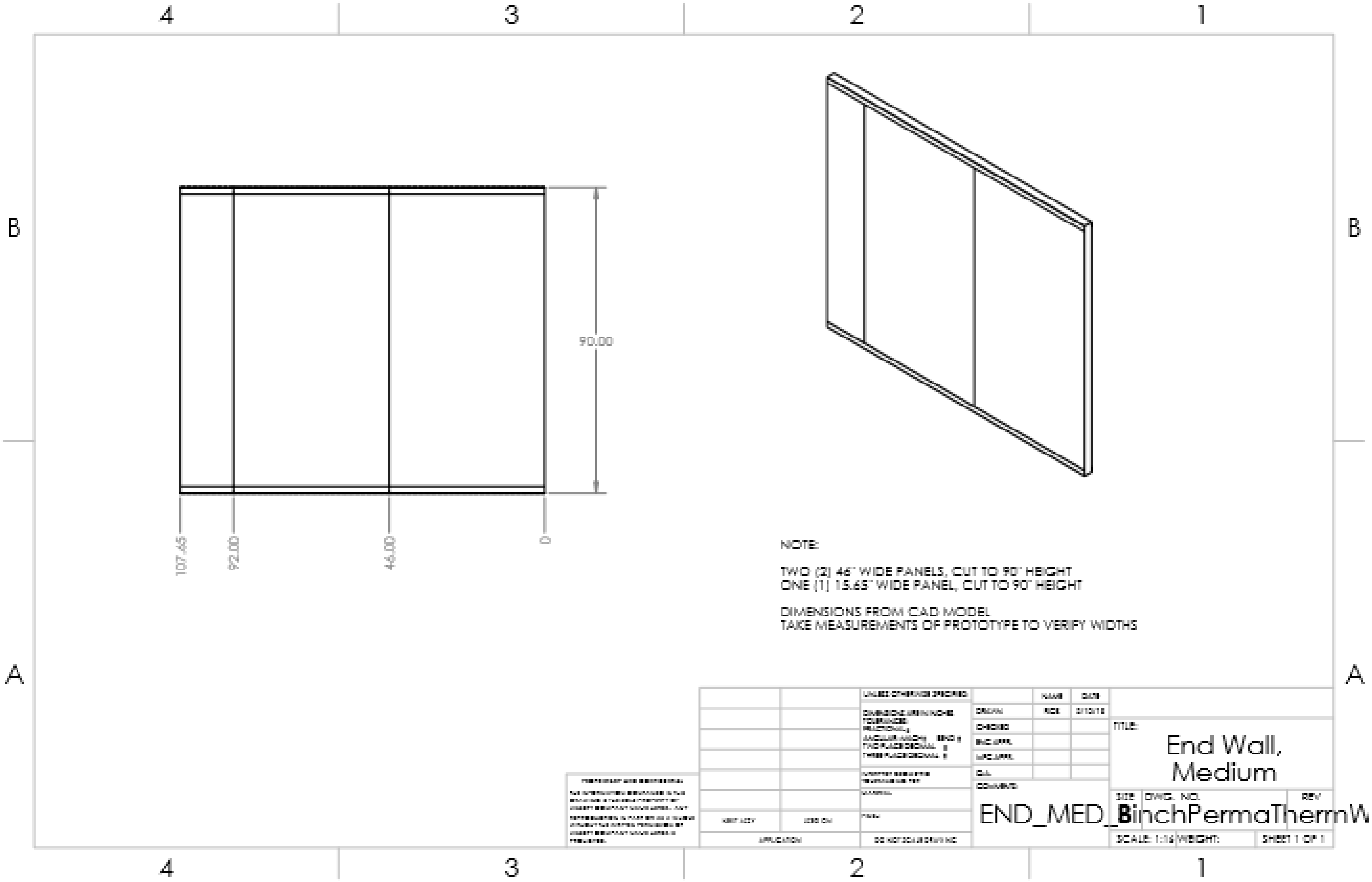

SMALL
LARGE
MEDIUM
99.82
93.32
0
84.02
179.00
269.00
96.57
120.00
Full Assembly



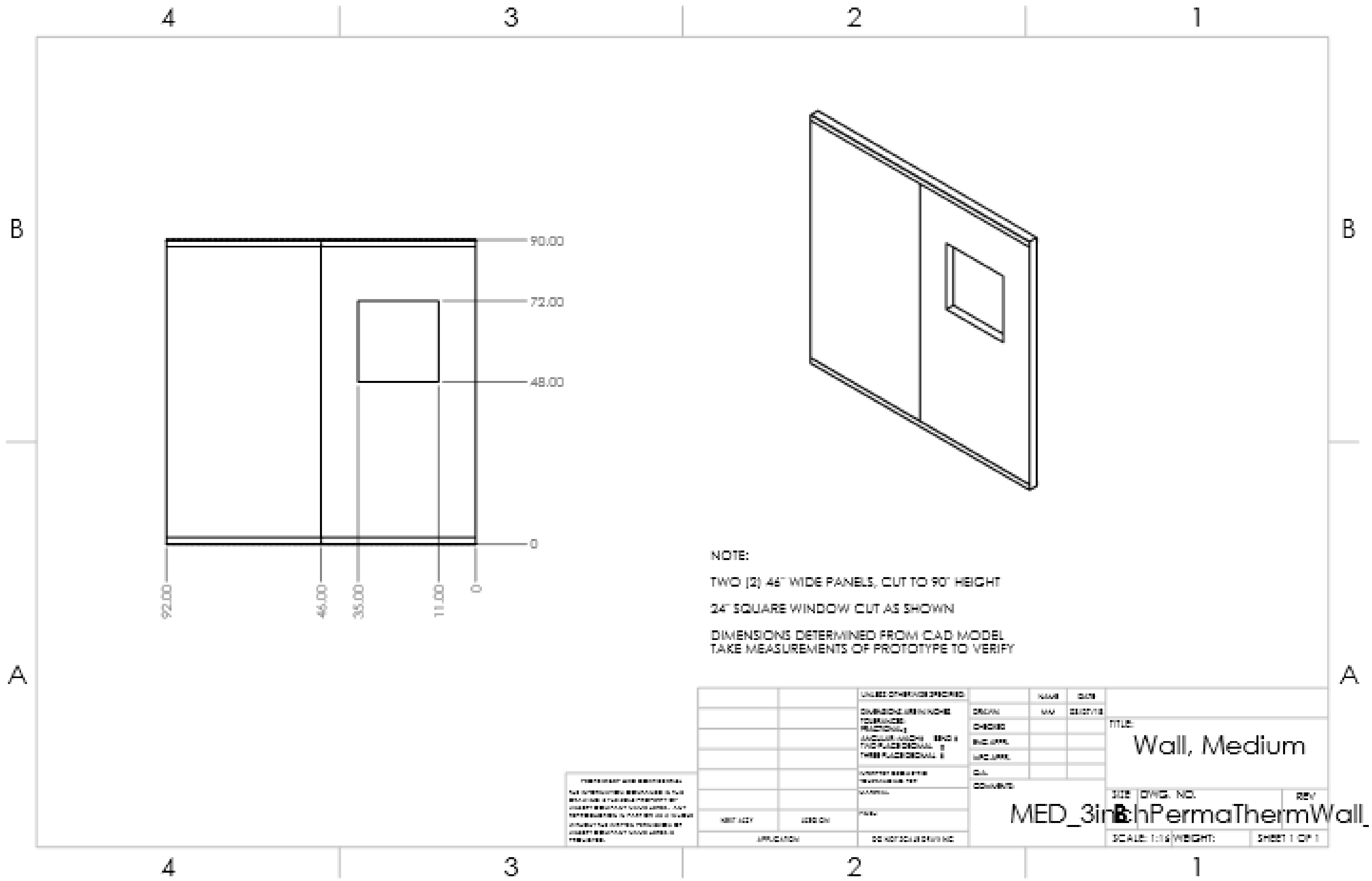
94.75
83.00
3.00
0
7.00
39.00
46.00
92.00
NOTE:
TWO (2) 46" WIDE PANELS, CUT TO 94.75" HEIGHT
32 X 80 " CUT FOR DOOR AS SHOWN
DIMENSIONS FROM CAD MODEL
TAKE MEASUREMENTS OF PROTOTYPE TO VERIFY WIDTHS
TITLE:
Wall, Large, Door
SIZE
B
DWG. NO.
3inchPermaThermWall_Door
REV
SHEET 1 OF 1


94.75
0
46.00
92.00
NOTE:
TWO (2) 46" WIDE PANELS, CUT TO 94.75" HEIGHT
DIMENSIONS FROM CAD MODEL
TAKE MEASUREMENTS OF PROTOTYPE TO VERIFY WIDTHS
TITLE:
Wall, Large, No Door
SIZE
B
DWG. NO.
3inchPermaThermWall_DF
REV
SCALE: 1:24
WEIGHT:
SHEET 1 OF 1
4
3
2
1
A
B

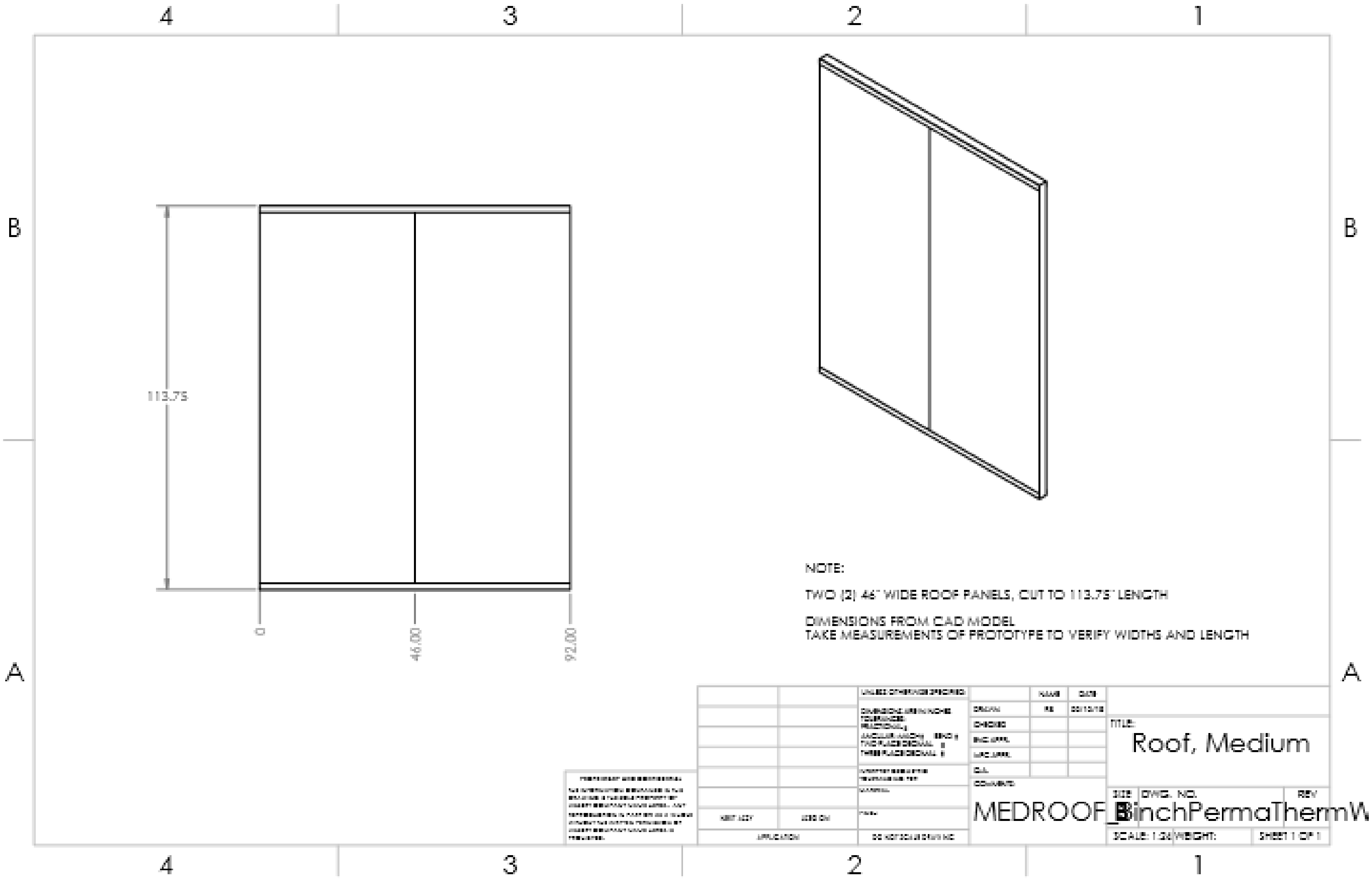

120.00
0
46.00
92.00
NOTE:
TWO (2) 46" WIDE ROOF PANELS, CUT TO 120" LENGTH
DIMENSIONS FROM CAD MODEL
TAKE MEASUREMENTS OF PROTOTYPE TO VERIFY WIDTH AND LENGTH
TITLE:
Roof, Large
SIZE
DWG. NO.
REV
LGROOF_3inchPermaThermW
SCALE: 1:24
WEIGHT:
SHEET 1 OF 1
4
3
2
1
A
B

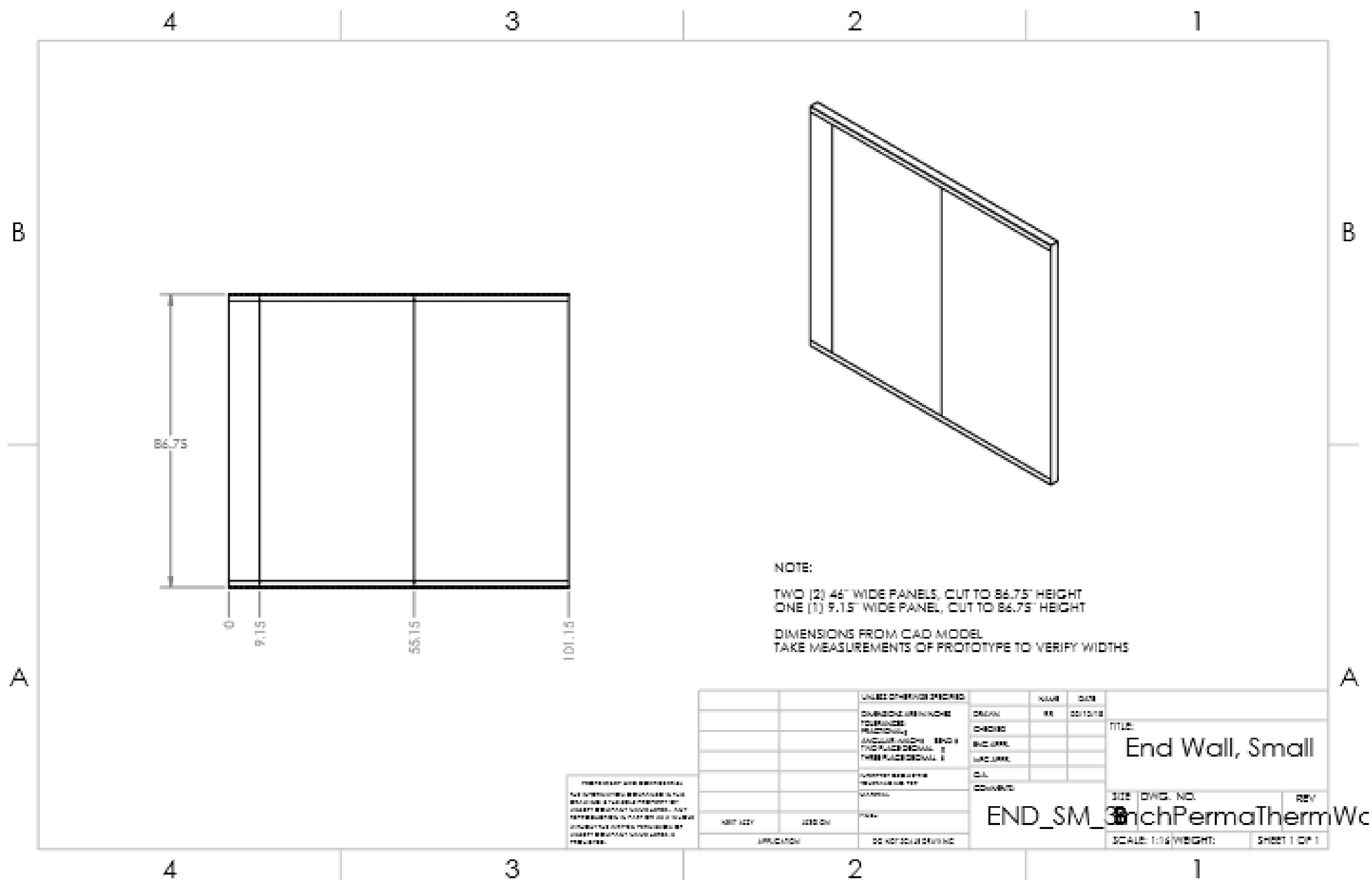


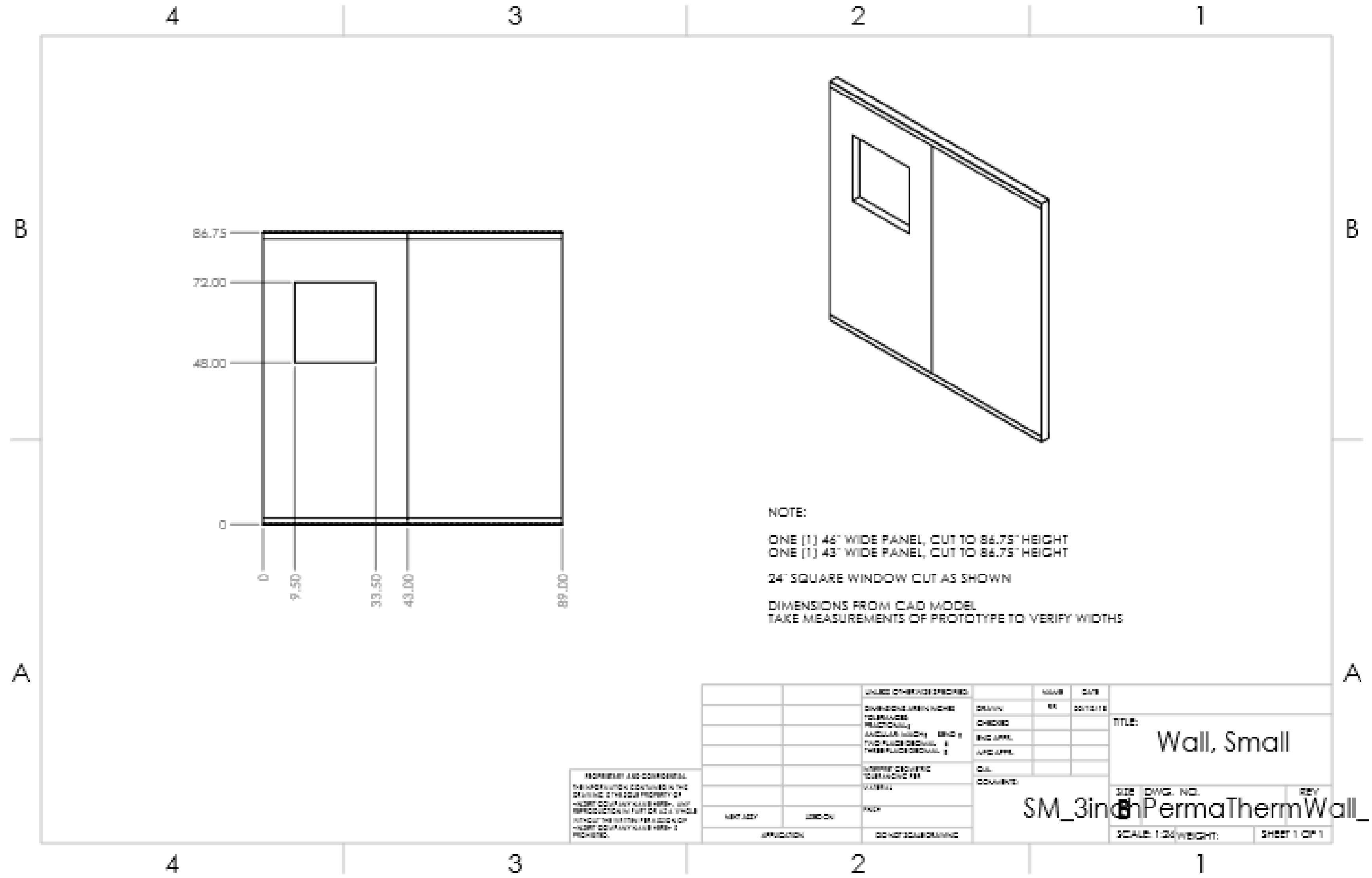
107.65
92.00
46.00
0
90.00
NOTE:
TWO (2) 46" WIDE PANELS, CUT TO 90" HEIGHT
ONE (1) 15.65" WIDE PANEL, CUT TO 90" HEIGHT
DIMENSIONS FROM CAD MODEL
TAKE MEASUREMENTS OF PROTOTYPE TO VERIFY WIDTHS
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
APPLICATION
DO NOT SCALE DRAWING
TITLE:
End Wall,
Medium
SIZE
DWG. NO.
REV
END_MED_BinchPermaThermW
SCALE: 1:16
WEIGHT:
SHEET 1 OF 1

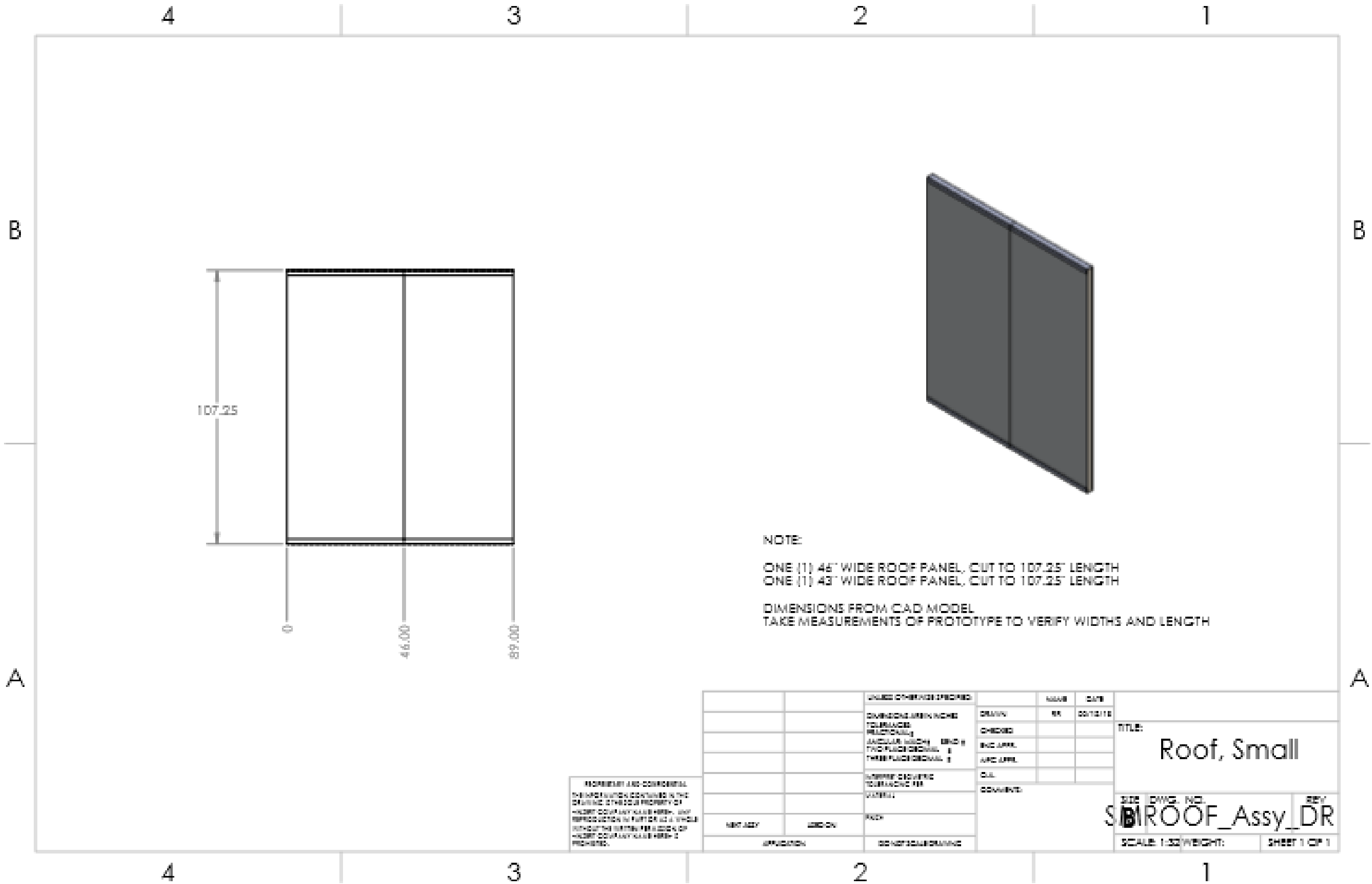


92.00
46.00
35.00
11.00
0
90.00
72.00
48.00
NOTE:
TWO (2) 46" WIDE PANELS, CUT TO 90" HEIGHT
24" SQUARE WINDOW CUT AS SHOWN
DIMENSIONS DETERMINED FROM CAD MODEL
TAKE MEASUREMENTS OF PROTOTYPE TO VERIFY
TITLE:
Wall, Medium
DWG. NO.
MED_3inchPermaThermWall_
REV
SIZE B
SHEET 1 OF 1


113.75
0
46.00
92.00
NOTE:
TWO (2) 46" WIDE ROOF PANELS, CUT TO 113.75" LENGTH
DIMENSIONS FROM CAD MODEL
TAKE MEASUREMENTS OF PROTOTYPE TO VERIFY WIDTHS AND LENGTH
TITLE:
Roof, Medium
SIZE
DWG. NO.
REV
MEDROOF_
inchPermaThermW
SCALE: 1:26
WEIGHT:
SHEET 1 OF 1


86.75
0
9.15
55.15
101.15
NOTE:
TWO (2) 46" WIDE PANELS, CUT TO 86.75" HEIGHT
ONE (1) 9.15" WIDE PANEL, CUT TO 86.75" HEIGHT
DIMENSIONS FROM CAD MODEL
TAKE MEASUREMENTS OF PROTOTYPE TO VERIFY WIDTHS
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
End Wall, Small
SIZE
DWG. NO.
REV
END_SM_3 InchPermaThermWc
SCALE: 1:16
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING


86.75
72.00
48.00
0
9.50
33.50
43.00
89.00
NOTE:
ONE [1] 46" WIDE PANEL, CUT TO 86.75" HEIGHT
ONE [1] 43" WIDE PANEL, CUT TO 86.75" HEIGHT
24" SQUARE WINDOW CUT AS SHOWN
DIMENSIONS FROM CAD MODEL
TAKE MEASUREMENTS OF PROTOTYPE TO VERIFY WIDTHS
TITLE:
Wall, Small
DWG. NO.
SM_3inchPermaThermWall_
SCALE: 1:24
WEIGHT:
SHEET 1 OF 1



107.25
0
46.00
89.00
NOTE:
ONE (1) 46" WIDE ROOF PANEL, CUT TO 107.25" LENGTH
ONE (1) 43" WIDE ROOF PANEL, CUT TO 107.25" LENGTH
DIMENSIONS FROM CAD MODEL
TAKE MEASUREMENTS OF PROTOTYPE TO VERIFY WIDTHS AND LENGTH
TITLE:
Roof, Small
SIZE
DWG. NO.
REV
B
ROOF_Assy_DR
SCALE: 1:32
WEIGHT:
SHEET 1 OF 1